UH-1 CORROSION MONITORING

A Thesis Proposal
Presented to
The Academic Faculty

By

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In Partial Fulfillment
Of the Requirements for the Degree
Master of Science in the
School of Aerospace Engineering

Georgia Institute of Technology
August 2010

UH-1 CORROSION MONITORING

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To my family, for their enduring encouragement.

ACKNOWLEDGEMENTS

I would like to thank my advisor Dr. Mavris and my supervisor Mr. Joseph Jones for allowing me this opportunity and keeping me on the right track throughout this project. I would also like to thank my committee members Dr. Schrage, and Dr. Volovoi for their patience and support. Without their insight I would still be wading through the mud, trying to establish my research foundation. I must also thank the rotary engineers at Robins AFB, for patiently reviewing my work and offering their expertise on aircraft structures. Thanks also to Analatom Inc. for providing very detailed information on their structural health monitoring systems. Finally, special thanks to my mom and brother for helping me get through and finish strong.

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ACE	Aircraft Condition Evaluation
AH	Attack Helicopter
ASIP	Aircraft Structural Integrity Program
AT	Action Taken
BCR	Benefits to Cost Ratio
CH	Cargo Helicopter
CI	Cost Index
CMS	Corrosion Monitoring System
CPI	Capability Index
DAQ	Data Acquisition Unit
FH	Flight Hours
HM	How Malfunctioned
HMMWV	High Mobility Multi-Purpose Wheeled Vehicle
IPPD	Integrated Product and Process Development
JCN	Job Control Number
LMH	Labor Man Hours
LPR	Linear Polarization Resistance
MFE	Model Fit Error
MI	Maintainability Index
MTBF	Mean Time Between Failure
MTBM	Mean Time Between Maintenance
MTTR	Mean Time To Repair
MTVR	Medium Tactical Vehicle Replacement

NDI	Non-Destructive Inspection
OEC	Overall Evaluation Criteria
OH	Observation Helicopter
QFD	Quality Function Deployment
RDT&E	Research Development Testing & Evaluation
RI	Reliability Index
TH	Training Helicopter
TOW	Time of Wetness
UH	Utility Helicopter
WI	Weight Index
WUC	Work Unit Code

SUMMARY

As the UH-1 aircraft continue to age, there is growing concern for their structural integrity. With corrosion damage becoming a bigger part of the sustainment picture with increasing maintenance burden and cost, it is becoming increasingly important for corrosion management to be updated with more advanced techniques.

Currently a reactive approach to corrosion is used, in which damage is dealt with on a find-and-fix basis. As a result, this current technique has several shortfalls. This has spurred the recent interest in early detection through structural health monitoring. This condition based technique is becoming more prevalent and is recognized for the potential to greatly reduce maintenance cost. Through corrosion monitoring, structural and environmental conditions can be closely observed, preventing excessive maintenance action and saving cost.

Searches for corrosion monitoring system designs revealed several commercial companies with prototype systems installed on commercial aircraft, however, details on system design and data analysis were scarce. This study attempted to bridge the gap in literature by providing insight into the development of a corrosion damage prediction model and the design of a corrosion monitoring system. Thus, this effort was divided into three main areas, structural evaluation, system design, and system implementation.

The first area, structural evaluation, involved analyzing aircraft maintenance data to determine the most problematic areas of the aircraft and the impact of aircraft location on corrosion damage. A method for analyzing maintenance information was developed that involved converting discrepancy information into numerical data that could be modeled. Variables of influence included time of wetness and sulfur dioxide concentration. Metrics of interest included the number of repairs, the number of replacements, the total labor man hours, total corrosion maintenance actions, and average repair time. Before the models were created, a screening test was performed for each variable. Results from the screening test identified that the average repair time metric did not have any significant variables. The remaining four metrics were

modeled using the significant variables identified by the screening test. The models were carefully analyzed for usability by examining the data spread, confidence intervals, correlation coefficients, residual spread, residual range, mean, and standard deviation. It was found that none of the models passed the evaluation. It was concluded that maintenance data alone was not enough to make a reliable prediction model. The impact of aircraft location on corrosion damage could therefore not be determined.

Although a reliable prediction model could not be created, trends observed in the data were still valuable for identifying problematic areas of the aircraft. It was found that replacements occurred twice as often as repairs, and took an average of twice as long to finish. This finding confirms that corrosion is a recurring problem that significantly impacts maintenance time and cost. The most problematic areas of the aircraft were also identified, in terms of frequency of maintenance actions as well as average repair time. The three worst areas were found to be the engine, tail boom, and center fuselage.

Utilizing a corrosion monitoring system can provide the accurate corrosion data needed for the development of better prognostic models. This can be accomplished through the implementation of a corrosion monitoring system. Problematic aircraft areas are prime candidates for monitoring, as they represent the majority of maintenance time and cost. Thus, system design was the second major effort in this investigation.

The Integrated Product and Process Development methodology was utilized to develop a custom corrosion monitoring system design for the UH-1 aircraft. The requirements for the system were developed both for the user and for the engineer. User requirements included capability, dependability, and feasibility. These requirements were broken down into specific areas that could be measured. Capability included sensitivity and sampling rate. Dependability included response time, mean time to repair, mean time between maintenance, and mean time between failure. Feasibility was captured by non-recurring cost, recurring cost and system weight. Target values were developed for each system attribute and relationships among requirements were shown in a quality function deployment.

System value was established by developing an index for each system attribute. The indices consisted of a ratio of the target value to the achieved value and would be used to evaluate the system design. An index greater than or equal to 1 would be ideal.

Available technology for each attribute of the system was found and used to construct a design concept. The design concept included linear polarization resistance sensors, a battery power source, a non-intrusive installation technique, time of wetness sensors, a permanent installation, a metal surface application, a data logger, a wireless method of data download, and off-line data retrieval. These attributes were represented by a commercial system, the Analatom AN101W corrosion monitoring system. The system consisted of 16 sensors, 2 data loggers, wiring, batteries, a wireless data download device, and associated software for data processing.

The system was evaluated using the indices, and it was found that the selected system met and exceeded the target values for each system attribute. Each index was either greater than or equal to 1, showing that the requirements for capability, dependability, and feasibility were met.

System implementation was the third area of study. System installation, system operation, and aircraft maintenance were considerations in this segment. Recommendations were made for both corrosion rate and atmospheric sensor placement on the UH-1 aircraft structure. 14 sensors were used to measure corrosion, and the remaining 2 sensors were placed to monitor the atmosphere in the aircraft. Data loggers were placed in a central location, out of the way of aircrews.

Impact of the system on aircraft operations was discussed, and it was found that the system would require 12 labor man hours per year. The CMS sensors and data loggers require no inspection, and thus time was only needed to download data from the system. Low recurring cost combined with a low acquisition cost make this system highly recommendable for UH-1 aircraft usage.

Once the system is implemented, several possibilities for inspection changes may emerge. Customized inspection intervals as well as reduced replacements will result in decreased maintenance burden and increased aircraft availability to meet warfighter needs. Once inspection intervals are customized, savings in maintenance effort and cost can be evaluated.

The selected commercial system proved to meet and exceed expectations, making it an ideal choice for the UH-1 aircraft. The system is not flawless, however, and several weaknesses have been identified. Despite system limitations, corrosion monitoring remains the next step in corrosion management, and will pave the way for more advanced corrosion management techniques. Through more advanced corrosion management techniques, the UH-1 aircraft will be safer and more available to meet growing warfighter needs.

CHAPTER 1: INTRODUCTION

1.1 UH-1: Past and Present

Helicopters have interested the military since World War I. While fixed wing aircraft were found to be very effective in military operation, there were obvious shortfalls that needed to be overcome. Fixed wing aircraft required well-kept runways, and a precise forward speed in order to take off and land. It was these limitations that spurred the development of vertical flight, with the first United States military helicopter project funded in 1921. [4]

There were many failed projects before the physics of vertical flight was sufficiently mastered to produce an aircraft that was usable for military operations. Each successful iteration of development yielded an aircraft that was faster and more effective than its predecessors. Eventually, helicopters were developed for specific applications and thus could be classified as an attack helicopter (AH), cargo helicopter (CH), observation helicopter (OH), training helicopter (TH), or utility helicopter (UH) [15].

Figure 1: UH-1H Aircraft [5]

The UH-1 helicopter, shown in Figure 1, is a utility aircraft that began service in 1956. Known as the “Huey”, Over 15,000 UH-1 aircraft have been manufactured and include many variants such as the A, B, C, D, E, F, H, N, P, V, and Y models. The H, V, and N models are the only Huey variants still in use by the Air Force today. These helicopters are light weight, spacious, and fast, making them a practical choice for a variety of operations, including small transport and search and rescue. [7]

1.2 Motivation

It is a well-known fact that the UH-1 aircraft are beyond their predicted service life. In fact, they are now more than four decades old. In addition, their utilization is more intense than what was intended by the manufacturer. As a result, the structure of the aircraft is worn at a faster rate than originally expected, essentially accelerating the aging process of the aircraft. For these reasons, the UH-1 helicopters are known as 'aging aircraft', and exhibit all of the structural issues of aircraft that have been used above and beyond the design service life. The result is an increased burden on aircraft sustainment operations both in terms of cost and maintenance effort, placing sustainment at the forefront of issues for these aircraft [12]. With no fleet retirement in sight, the UH-1 must last in order for operations to continue.

Structural issues for aging aircraft commonly appear in the form of fatigue cracking and corrosion [8] [12]. Fatigue is the damage of a material that occurs as a result of cyclic loading. Eventually, a crack initiates and grows until the material fractures. Corrosion, on the other hand, results from a chemical reaction between a material and the environment [9]. Like fatigue, corrosion weakens the material and ultimately, causes failure in the structure of the aircraft.

Failure prediction involves the concept of damage tolerance. Damage tolerance analysis involves finding the amount of time between crack initiation and propagation to a critical crack length. Inspection intervals are timed such that a crack could be found before it reaches critical length and causes the structural member to fail [8]. Unfortunately, in the era in which the UH-1 aircraft were designed, damage tolerance analysis did not take into account corrosion damage [62]. As a result of corrosion, the life of the part that was predicted through the damage tolerance analysis will be significantly reduced.

1.2.1 Corrosion Damage on the Rise

Corrosion has been a costly problem for the Air Force. According to the 2009 Cost of Corrosion Report, the United States Air Force spends an annual $5.4 billion dealing with missile and aircraft corrosion [2]; a number that only seems to increase with time.

“Over the next 20 years, the further aging of aircraft that are already old will introduce daunting challenges for aircraft operators, including the USAF, which is one of the world’s largest operators of old aircraft,” suggested RAND, a research corporation [12].

Period		Developments Related to the Aging of Aircraft: Technical	Developments Related to the Aging of Aircraft: Institutional
U.S. Army period	1907–1947	Military applications of aviation Wooden frames with fabric covering Aluminum alloys	Aviation industry Military aviation
U.S. Air Force periods (15 years each)	1. 1948–1962	Stronger metals Problem with durability Problem with catastrophic structural failures	Air Force established Aircraft Structural Integrity Program FAA established fail-safe requirements
	2. 1963–1977	Catastrophic structural failures at unacceptable level by 1970	Through 1970s, the Air Force switched to fracture-mechanics for managing its toleration of fatigue cracks (AFR 80-13, MIL-STD 1530A, MIL-A 83444)
	3. 1978–1992	Catastrophic structural failures very rare Rising corrosion-related costs Economic problem with widespread fatigue cracking	Acquisition streamlining consolidated reviews to two levels in mid 1980s Oversight reviews for managing toleration of fatigue cracks was reduced
	4. 1993–2007	Corrosion repair and maintenance affected costs and availabity of aircraft Catastrophic structural failures still rare, but rate may be starting to rise	ASIP regulation (AFR 80-13), military standard (MIL-STD 1530A) and military specs rescinded and replaced by Air Force Instruction (AFI 63-1001) and Policy Directive (AFPD 63-10) AFPD 63-10 directs system program director to tailor use of ASIP practices to program’s needs MIL-STD 1530C issued as statement of ASIP standard practices in 2005

Figure 2: Air Force Aging Aircraft History [12]

Figure 2 displays the evolution of Air Force aging aircraft structural concerns dating back to 1907. Beginning in 1978, corrosion began to pose problems for structural components, resulting in an increased cost for sustainment. After 1993, concern for corrosion damage evolved into concern for increased catastrophic failures, as the impact of corrosion on safety is recognized. This increase in concern for aging aircraft structure prompted recent attention on the Aircraft Condition Evaluation (ACE) and Air Force Aircraft Structural Integrity Programs (ASIP).

ACE inspections are a periodic evaluation of the condition of each aircraft, in an effort to rank order all aircraft in a fleet according to their structural condition. This inspection also identifies aircraft that are in the greatest need for depot level maintenance. While this inspection includes many condition evaluations for aircraft structure, corrosion was not always among them. It was not until 1997 that corrosion indicators, or identification codes, were implemented for use during ACE inspections [60].

A memorandum released in December 2009 by the Office of the Assistant Secretary emphasized the necessity of robust and effective ASIP programs, in light of "recent structural issues" [25]. This memorandum also reiterated the need to establish, evaluate, and substantiate aircraft structural integrity. The goal in dealing with corrosion is to minimize maintenance cost, while keeping the aircraft safe to fly [24].

Corrosion damage has several negative impacts, including [27]:

- Unplanned aircraft downtime
- Loss of aircraft parts
- Loss of maintenance efficiency and increased maintenance costs
- Unsafe conditions for pilots and aircrews

The most significant consequence is unexpected failure of a critical component in flight, resulting in unsafe conditions for aircrew and passengers. Not only is corrosion a growing problem for maintenance, but it is also an increasing safety issue.

1.2.2 Catastrophic Corrosion Failures

History has shown that corrosion damage is not to be taken lightly. The growing reality is that corrosion can lead to cracks in critical structural members, resulting in catastrophic aircraft failures. Catastrophic failures are accidents resulting in loss of the aircraft, aircrew, and even innocent bystanders. Several such events in the past have helped to shed light on the importance of corrosion in structural integrity.

Perhaps the most famous example of a catastrophic failure occurred in 1988 when a Boeing 747, operated by Aloha Airlines, lost a major portion of the aircraft structure due to corrosion pillowing in the fuselage lap joints. Figure 3 shows the damaged area of the aircraft. Miraculously, all passengers survived, however there was one crewmember casualty. [22]

Figure 3: Aloha Airline Accident [18]

In 1992, an EL AL 747 cargo aircraft experienced corrosion cracking and fatigue in the fuse pins that are responsible for connecting the engine structure to the wing. As a result, the aircraft lost the number 3 engine. When the number 3 engine broke from the wing, it caused the number 4 engine, which also had a fuse pin weakened by corrosion, to also separate. With both engines gone from one wing as well as damaged control surfaces, the pilots could not maintain control over the aircraft.

Figure 4: EL AL Accident

Forty three people were killed when the aircraft crashed into an apartment building in Amsterdam, Netherlands. Figure 4 shows a computer simulation of the accident (left) and the resulting damage to the housing area (right). The same corrosion cracking in the fuse pins caused a China Airlines 747 freighter to crash in the same manner only a year prior. [9]

Five F-16 fighter aircraft crashes, in which the main fuel shut off valves closed without command, were determined to have been caused by fretting corrosion between two dissimilar metals in an electrical connection. The nearly invisible corrosion damage was only found after the connection was inspected by a trained corrosion engineer. [20]

These examples show that it only takes corrosion causing the failure of one critical component, to lead to a catastrophic incident. In order to prevent future accidents, it has become necessary for corrosion management to evolve beyond current practices and incorporate advanced mitigation techniques.

1.3 Corrosion Mitigation Techniques

Currently a reactive approach to corrosion is used, in which damage is dealt with on a find-and-fix basis. Corrosion inspections are normally qualitative, and the assessment of the structure is highly dependent on the examiner. As a result, this current technique has several shortfalls. The examiner's experience may be limited, there is a constant fluctuation of corrosive conditions, and corrosion damage often occurs in hidden areas of the aircraft. [61]

These limitations have spurred the exploration of corrosion mitigation. There are several methods of corrosion mitigation, including:

- Building corrosion resistance into the design of the aircraft.
- Slowing the progression of corrosion damage through protective finishes or controlling the environment or geographical location in which the aircraft operates [32].
- Monitoring the progress of corrosion through early detection [32].

While it is recommended that corrosion be controlled through all three venues, due to the age of the UH-1 aircraft, only the second and third options are applicable. This is due to the lack of corrosion prevention technology in aircraft design at the time the UH-1 was produced. Protective finishes or coatings, referred to as corrosion prevention compounds, are currently in widespread use, however, early detection of corrosion damage for critical components is an avenue that is only recently being explored for aircraft implementation.

As maintenance practices evolve from find-and-fix toward condition-based, early detection through aircraft structural health monitoring becomes more important. Health and usage monitoring systems gather data about the usage of the aircraft, as well as vibration data, in an effort to predict maintenance actions and prevent component failures. These health monitoring systems are based upon the principle that structural performance has a close relationship to structural health [34]. Health and usage monitoring systems have been implemented on several US military rotorcraft, including the UH-60, AH-64, MH-53, and the OH-58D. The Air Force reported a 95% reduction in mission aborts related to vibration problems as a result of implementing this type of system on the MH-53. [69]

Detecting corrosion in its early stages, as part of a health monitoring system, will reduce damage to aircraft components by providing the opportunity of fixing the problem before it significantly affects a component or spreads to other aircraft parts [12]. This reduction in damage equates to a reduction in the cost of maintenance and replacement parts.

1.4 Corrosion Monitoring

Corrosion has been a problem ever since our ancestors began working with metal. Even the Roman Army experienced firsthand the detrimental effects of corrosion, when numerous arbalests failed, causing casualties in their own army [14]. Unfortunately, this wasn't the end of corrosion problems for the Roman Empire. Lead, a common lining used in containers for alcoholic beverages, tended to corrode away –

leaving it to be consumed by the Roman hierarchy [26]. This resulted, as some believe, in the end of the Roman Empire [26].

While technology may have advanced considerably from Roman times, the problem with corrosion has always remained the same. Corrosion eats away at structural components, leaving them susceptible to failure. That is why billions of dollars are spent each year in an attempt to preserve aging structures of all types; from bridges and buildings to ships and aircraft.

Implementing corrosion monitoring has three major benefits:

- Streamline maintenance effort [17].
- Reduce unplanned maintenance and aircraft downtime [17][34].
- Supply data for further study [17].

With a corrosion monitoring system, structural components can be inspected when needed, effectively streamlining maintenance effort. Because there is constant knowledge of the current state of the structure, unplanned maintenance as a result of unexpected failures is reduced. With unexpected failures reduced, aircraft safety is increased. Lastly, data gathered from the monitoring system can assist in the next advancement in corrosion management - corrosion prediction models. It has been conjectured that using damage monitoring systems in transportation applications, such as roads, bridges, and aircraft, can result in a 20% reduction in maintenance cost [34].

Military aircraft are not the only applications that can potentially benefit from a corrosion monitoring system. Research suggests that similar monitoring systems are being developed for use in civil structures. The structural integrity of a bridge, for example, is critical to the safety of travelers. Monitoring structural health, including corrosion damage, is a very valuable tool in assessing the current structural condition of the bridges. With new technology in hand, “smart” monitoring systems are in development and include the use of sensors and wireless data transmission. [35]

In order to benefit from a corrosion monitoring system, understanding corrosion damage on an individual aircraft basis is essential [12]. With Air Force aircraft operating in different climatic regions, the structure is exposed to varying corrosive environments. Because of this climate variation and usage variation experienced by different air bases, it is not sufficient to consider the corrosion damage of one aircraft and assume it to be representative of the entire fleet.

Through a corrosion monitoring system, damage caused to the UH-1 aircraft structure can be mitigated before becoming a safety hazard, and maintenance practices can be further streamlined with the reduction of unplanned aircraft maintenance.

1.5 Literature Review

In an effort to gain an understanding for corrosion monitoring, a variety of topics was researched. Only a small selection of literature is presented here, in an effort to show the current state of corrosion monitoring. The first area of interest is the analysis of corrosion damage using aircraft maintenance data.

Several studies were found in which aircraft maintenance data was analyzed in order to determine aircraft parts that were most often attacked by corrosion, four of which are discussed here. In 1997, Wright Laboratory released a study of corrosion and fatigue cracking on USAF aircraft. Maintenance data was gathered and evaluated and used to create databases for the C/KC-135, E-8C, C-130, and C-5A/B aircraft. The database was then queried for different principal structural elements (PSE's) and records were counted for defect codes CN, for corrosion, and CK, for cracks. PSE's with high occurrences were identified as needing further consideration. Among all four of the aircraft fleets that were analyzed, the aircraft skin had the highest number of records. One shortfall of the databases was observed to be the quality of the data. Comments entered into the maintenance database can be inconsistent and incomplete. One recommendation of this study is to utilize a smart data entry system as well as standardizing work area and zone codes to improve consistency among maintenance comments and codes. With these improvements, trends in corrosion and crack damage can be made with increased confidence. [67]

In 2002, an Army study for ACE inspection improvement for various rotary aircraft was performed. ACE corrosion findings for UH-60, CH-47, AH-64, and OH-58 rotary aircraft were analyzed. New ACE corrosion indicators were developed for the UH-60 aircraft and weights for each indicator were suggested. A ranking of most severely damaged parts for each mission design series was developed based on the number of corrosion "hits" experienced by each structural indicator. For the UH-60, the cabin door frames, tracks, and latch keeps had the highest number of occurrences, and the tail cone interior held the second highest hits. For the AH-64, the engine mounts and canopy structure and doors represented the biggest problem with corrosion damage. CH-47 aircraft had the most problems with the forward and aft upper walkway honeycomb panels and the OH-58 aircraft had frequent corrosion damage on the passenger and co-pilot lower shell. The study concluded that many of the corrosion problems detected during the ACE inspections were costly and preventable and the addition of a separate index for corrosion is very valuable in the scoring of corrosion damage. The next step was recommended to be a more detailed analysis in order to make the appropriate changes to improve aircraft corrosion resistance. [60]

In 2009, a Marine Corp study identified commonly corroding parts of ground vehicles. Data was collected during the time span from 1997 through 2008 for parts that impact maintenance costs through item cost, cumulative quantity cost, labor cost, or excessive downtime. A searchable database was created using this information. For several categories, lists were prioritized for two cases, total replacements, and total part cost. Categories included Medium Tactical Vehicle Replacement (MTVR), High Mobility Multi-Purpose Wheeled Vehicle (HMMWV), material handling equipment, air conditioning, combat engineering equipment, generators, light assault vehicle, and heavy combat equipment. The study recommended that common wording among similar parts be created, for more consistent maintenance data. It was also suggested that the actual reasons for failure among the parts be found, to assist in determining if a problem is "economically correctable". [65]

In 2009, a Navy study determined the effect of wash cycle on P3 aircraft corrosion damage. The study was motivated by a desire to increase aircraft availability, and reduce costs associated with frequent aircraft wash cycles. Two wash intervals, 28 day and 112 day, were investigated. Data was gathered from 10 corrosion sensors placed on 14 aircraft. Sensors were placed both inside and outside of the aircraft. Sensor data was collected every three months for the duration of one year. An interesting observation was that each aircraft had its own unique response “signature”. The cause of this effect is speculated to be the slight difference in usage for each aircraft. It was concluded that there was no significant difference in corrosion damage between the two wash cycles. As a result, the study recommended extending the wash intervals to reduce cost and increase aircraft availability. It was also recommended further study to be done in order to optimize aircraft wash cycles. [63]

Literature was also gathered on the design of a corrosion monitoring system. In 2009 a conference paper was presented involving the design of a remote structural health monitoring system for military steel bridges. The motivation behind this study was to reduce the risk of a catastrophic failure by providing advanced warning of corrosion/material degradation. While the bridged were inspected regularly using several non-destructive inspection techniques, they were not sufficient to detect cracks on hidden structural members. Corrosion damage combined with metal fatigue drastically accelerates degradation of structural integrity. Two steel bridges were chosen for a monitoring system. This study was broken down into three main areas: structural evaluation, sensor selection, and system design. The structural evaluation, involving the review of maintenance reports and loads analyses, provided candidate locations for sensor placement. Sensor selection was based on current technology and commercial products. The system includes a data recorder and analysis system, and a remote computer for data storage. The system tracks all sensors and transmits a warning when a problem is detected. [64]

Also of interest for this study are prototype corrosion monitoring system installations on commercial and military aircraft. Three studies were found and are discussed briefly here. In the first study, in 2002, a corrosive environment monitoring system was developed by Honeywell and the US Army Aviation Applied Technology Directorate. The system measures the environmental conditions inside the aircraft. The system is divided into two modules which are connected via a single cable. The first module contains the sensors for measuring the environment, and the second module, the electronics and support module, displays current conditions to the user. The sensor module can be placed in an inaccessible part of the aircraft and the support module can be placed in an easily accessible location. The entire system operates from four AA batteries and records data at the rate of one sample per hour. At the time this report was released, one system had been installed on a CH-47D, with four more installations planned. Predicted benefits include a decrease in operations and support costs and an increase in aircraft availability. [59]

Other installations of a corrosion monitoring system include a Boeing 747 installation by CSIRO, an Australian company, in 2007 [68], and an installation of a corrosion/stress monitoring package on a Sabreliner Model 40 business jet in 2009 [10].

While several sources suggested that a corrosion monitoring system would reduce cost and maintenance effort, only one source was found that quantified the benefits of implementation. This source identified a potential 20% reduction in maintenance cost [34].

1.6 Observations

Several observations were made from the selected literature presented throughout this report.

1. An increase in corrosion damage for aging structures has driven up sustainment effort necessary to keep aircraft safe and operational.
2. Current inspection techniques are inadequate for assessing the condition of hidden structural members.
3. Early detection is the next logical step in corrosion management and is currently being explored by several commercial entities.
4. Corrosion models are typically developed in laboratories, with test coupons and controlled atmospheres. While these models give important information on corrosion rates, it is difficult to predict damage on aircraft with a variety of operating conditions.

5. Maintenance data can be used to identify problem parts and candidate sensor locations, although the comments are often incomplete and inconsistent.
6. Savings in maintenance effort should outweigh the cost of implementing a monitoring system, and the ultimate result will be the increased availability of the aircraft, although this has not yet been quantified.
7. When multiple aircraft are outfitted with the same corrosion sensors, each aircraft has its own unique signature, suggesting that corrosion monitoring should be done on an individual aircraft basis.
8. Corrosion monitoring systems are generally composed of a group of sensors, a data acquisition unit, and a method of processing data.

1.7 Research Questions

Review of literature on corrosion theory and aircraft corrosion damage have prompted several research questions. These questions assisted in defining the scope of this effort as well as the desired goals of data analysis.

1. What method is appropriate for analyzing maintenance information?
    a. How can the information be converted to analyzable data?
    b. What areas of the UH-1 aircraft have the most problems with corrosion?
    c. What are the metrics of interest and variables of influence?
    d. Does the location of aircraft operation have an impact on corrosion damage?
2. What corrosion monitoring system design would be most beneficial to the UH-1 aircraft?
    a. What are the requirements for a corrosion monitoring system?
    b. What technology is available for use?
3. What impact will a corrosion monitoring system have on maintenance operations?
    a. What savings in maintenance effort and cost will be observed as a result of implementing the monitoring system?

b. What changes in maintenance inspection intervals or techniques will be observed as a result of implementing a monitoring system?

1.8 Technical Approach

Intermediate-level maintenance data will be used to develop a prediction model for UH-1 corrosion damage and to custom design a corrosion monitoring system for the UH-1 aircraft.

1.9 Research Scope

The proposed research can be divided into two major parts, structural evaluation and system design.

1.9.1 Structural Evaluation

Structural evaluation was accomplished through the analysis of maintenance data for corrosion damage for the UH-1 aircraft currently in service with the Air Force. Structural problem areas, as determined by the maintenance data, were prime candidates for corrosion sensor placement. Consideration was also placed on the areas of the aircraft that are not easily accessible for inspection. In addition, corrosion damage was compared for different climate areas, in an effort to determine whether location had an influence on the observed damage.

Scope: Evaluate 6 years of intermediate-level maintenance data.

Objective: Locate corrosion problem areas on the UH-1 aircraft and investigate potential correlation between corrosion damage and aircraft operating location.

1.9.2 System Design

Part two of this effort involves the custom design of a corrosion monitoring system for the UH-1 aircraft. System requirements were developed and a functional analysis was performed. Target values were established for the system and an overall evaluation criteria was developed. A design was chosen among alternatives and a cost benefits analysis was completed. The final result was compared with the original system requirements and recommendations on sensor installation were made.

Scope: Design a monitoring system for the UH-1 aircraft that meets user requirements.

Objective: Evaluate system costs and benefits.

1.10 Assumptions and Limitations

There were several limitations and assumptions used in this investigation. Many limitations were a result of using maintenance data. Firstly, data that was gathered spanned a six year period. As a result, the corrosion condition for each aircraft up to that point was unknown. Secondly, maintenance comments were input by hand and vary by individual, causing many entries to be ambiguous. Thirdly, corrosion was identified by its effect, not its type. For example, damage may be identified as a “powdery substance” or “bubbling paint” as opposed to pitting or exfoliation. This limited the information that could be obtained from the comments.

Several assumptions were made for this effort. Firstly, it was assumed that the aircraft operate near their assigned base. Climate conditions experienced by the aircraft were assumed to be the same as experienced by the base. Secondly, the differences between UH-1H/V and UH-1N structure were taken as negligible. This allowed the UH-1H aircraft to be representative of the UH-1 fleet, although there are some structural differences between the two.

1.11 Summary

The UH-1 helicopter has been in service for over forty years, and is still a critical part of small transport and search and rescue operations. The UH-1 is well beyond its originally intended service life and exhibits structural issues that are typical of an aging aircraft. Corrosion represents a major impact on sustainment for the aging structure. The United States spends billions of dollars annually to correct problems caused by corrosion damage.

Corrosion has several negative impacts on operations, including increased aircraft downtime, and increased maintenance labor and cost. Not only is corrosion a growing problem for maintenance crews, it is also an increasing safety issue. Corrosion can lead to cracks in critical structural members, resulting in catastrophic aircraft failures. The EL AL and Aloha Airlines accidents are a grim reminder of the importance of corrosion management. In order to prevent future accidents, it has become necessary for corrosion management to evolve beyond current practices and incorporate advanced mitigation techniques.

One such mitigation technique involves monitoring corrosion through early detection. Early detection provides the opportunity to correct corrosion before it becomes significant. Implementing corrosion monitoring has the potential to reduce aircraft down time and maintenance labor needed to correct damage caused by corrosion.

Literature has shown several uses for corrosion monitoring, including prototype installations. While sources point out the benefits of implementing a corrosion monitoring system, there is little insight into the system design or the exact maintenance benefits that would be experienced after implementation.

This thesis attempts to bridge the gap in literature by providing two efforts. The first is a structural evaluation of the UH-1 aircraft, using aircraft maintenance data over a six year period. The objective is to locate corrosion problem areas on the UH-1 aircraft and investigate potential correlation between corrosion damage and aircraft operating location. The second part of the effort involves the custom design of a corrosion monitoring system for the UH-1. The objective is to design a system that met user requirements. These two tasks represent the bulk of this investigation. In order to embark on these objectives, it is important to first investigate the background of corrosion.

CHAPTER 2: CORROSION BACKGROUND

2.1 How Corrosion Forms

Corrosion has been recognized as a major problem impacting aging structure. By definition, corrosion is an electrochemical reaction between a material and the environment [9]. Corrosion formation begins with a simple electrical circuit, or cell. An example of a corrosion cell, in which iron is rusting in the presence of water, is shown in Figure 5.

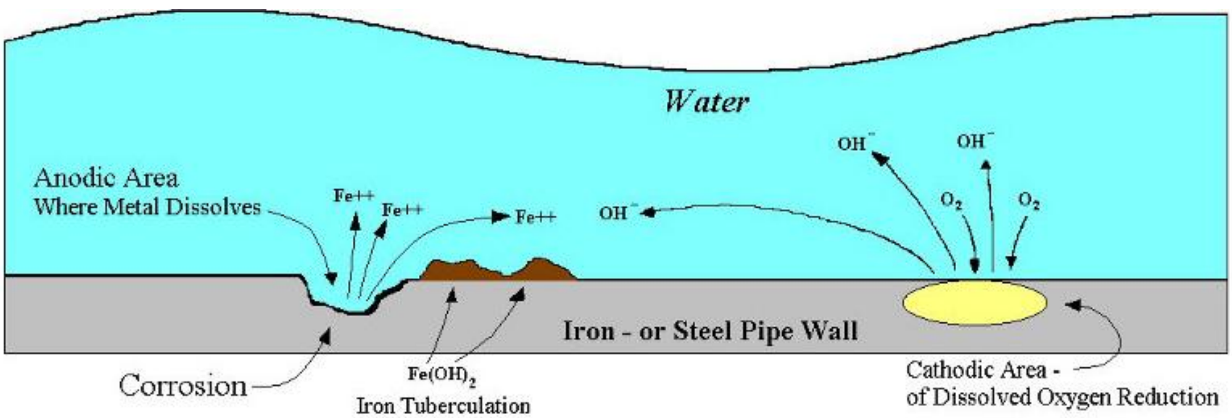


Figure 5: Corrosion Cell Example [29]

Like a battery, a corrosion cell includes four basic elements. Disruption of any one of these essential elements will prevent the corrosion cell from forming, as it would prevent the battery from providing power [28]. This is the basis on which corrosion prevention compounds are developed. The four basic elements of a corrosion cell are listed as follows [27][28]:

- Anode – negative terminal and site where the afflicted part loses material
- Cathode – positive terminal
- Electrolyte – solution that allows for exchange of electrons
- Metallic Path – electrical path connecting the anode and cathode

The presence of an anode and cathode is the driving force behind the transfer of electrons. As in a battery cell, an electrolyte is necessary for the exchange of electrons. The electrolyte may vary in concentration, depending on what it is comprised of, and as a result, will have varying effects on the rate of corrosion damage. The metallic path completes the electrical circuit, allowing the oxidation reduction reaction to continue.

Electrolytes can consist of many different dissolved substances, and will vary depending on the operating conditions of the aircraft. For example, an aircraft operating mostly in marine atmospheres will have electrolyte solutions composed of salt spray. An aircraft operating in the desert may have electrolyte solutions made from dirt and salt. All aircraft are liable to have dissolved solutions of acidic gases from pollution as well as engine exhaust gases. [32]

2.2 Factors of Influence

Several factors are involved in the formation of corrosion and will tend to dictate the type of corrosion, rate of corrosion damage, and location at which the material experiences a corrosion attack. The variables of corrosion include stress, material properties, and the environment. [9]

Stress factors include the stress that the metal component experiences, in the form of applied mechanical stress or the residual stress from the manufacturing process. [32]

Material properties include the type of metal being attacked, the quality of heat treatment performed, and the grain direction of the material [32]. The corrosion oxidation-reduction reaction causes the material to revert back to its oxidized state, the state in which it was in before being manufactured into the metal component that is on the aircraft.

Environmental factors include temperature, humidity, air-borne contaminants, cathode and anode size, the strength of concentration of the electrolyte, how much oxygen is readily available, whether organisms are present, and how long the metal is exposed to a potentially corrosive environment. In general, an increase in any of these factors will result in the acceleration of corrosion damage. This is especially true for temperature, in which a 10°C increase will double the reaction rate. [32]

For this study, the operating environment of the aircraft received great consideration, as this would dictate many of the factors influencing corrosion formation. Corrosion that is primarily influenced by the atmospheric conditions varies depending on several general conditions [9][17][27]:

- Temperature
- Moisture
- Contaminants

The UH-1 fleet includes aircraft located in different regions across the United States. This will cause the corrosive effects of the atmosphere to vary, depending on the aircraft location. The environment is difficult to predict, and varies from day to day. Thus corrosion damage will vary with these environmental factors. This complication can be mitigated through the monitoring of atmospheric conditions such as temperature and humidity. This can be accomplished with sensors separate from the corrosion monitoring sensors that are responsible for measuring atmospheric factors. While atmospheric data may seem unnecessary, as more data is gathered from the corrosion sensors, trends can be identified and possibly linked to the atmospheric conditions, allowing for development of corrosion prediction models.

2.3 Technical Challenges

Corrosion has proven to be a highly unpredictable phenomenon. It has many variants and will form at any location with the right conditions. To complicate the matter further, the type of damage that is experienced by the part depends on the type of corrosion that formed. Corrosion tends to couple with other forms of failure, such as fatigue cracking. It is not uncommon to see a failure with evidence of both fatigue cracking and corrosion [14], in which corrosion weakens the material, making it more susceptible to fatigue cracking and failure.

2.3.1 Corrosion Prone Areas

As previously mentioned, corrosion will form anywhere in which the four required conditions are met (anode, cathode, electrolyte, and metallic path). Corrosion tends to be attracted to minor imperfections on a material's surface such as folds, inclusions, internal stresses, and at localized damage areas such as crevices and cracks [28]. Corrosion is also attracted to confined inaccessible areas [32], causing these areas to corrode very rapidly.

Table 1: Typical Corrosion Prone Areas

• Engine inlets and exhaust trail areas	• Electronic compartments and equipment
• Battery compartments and battery vents	• Spot-welded assemblies
• Wheel wells and landing gear	• Fasteners
• Bilge areas	• Faying surfaces and crevices
• Drain areas	• Control Surfaces
• Hinges	• Control cables

A list of corrosion prone areas was compiled using information from the American Society of Nondestructive Testing [28], the Federal Aviation Administration [32], and the Air Force Corrosion Prevention and Control Technical Manual [37]. These areas, shown in Table 1, were of particular interest while examining maintenance data for the UH-1 aircraft.

Just as there are many areas in which corrosion can form, there are an abundant array of different types of corrosion that can form, as discussed in the next section.

2.3.2 Corrosion Types

Table 2 shows numerous types of corrosion damage. A general understanding of the various corrosion types is needed in order to choose appropriate sensors and locations for the corrosion monitoring system. A brief discussion on each type is provided in Table 2 for quick reference.

Table 2: Corrosion Types


Figure 6: Uniform [42]

Uniform Corrosion – the component surface experiences a constant rate of thickness loss. Damage is evenly spread over the surface. This form of corrosion tends to be the most predictable and can be easily modeled using the atmospheric conditions and material type. [30]


Figure 7: Galvanic [43]

Galvanic Corrosion – the result of two dissimilar metals making contact in an electrolyte solution. The innate nature of the material determines its resistance to this type of corrosion. In general, the more noble the metal, the less likely the material is to corrode. [30]


Figure 8: Pitting [44]

Pitting Corrosion – A localized 'pit' like material loss. This form of corrosion can lead to cracking due to the weakened state of the material, even though the pits are small in size. Material defects can initiate pitting corrosion and once a pit forms, it grows at an increasing rate. [30]

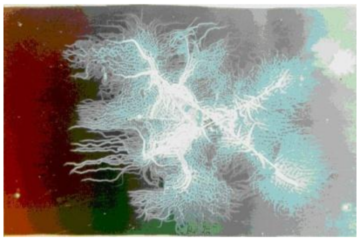


Figure 9: Filiform [39]

Filiform Corrosion – Corrosion of this type is characterized by its worm-like shape. Once moisture intrudes in the coating, the corrosion forms from a small coating defect, then branches out as it spreads beneath the layer of paint. [39]

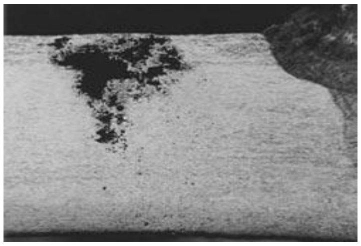


Figure 10: Intergranular [46]

Intergranular Corrosion – This type of corrosion results in a localized attack on grain boundaries and nearby areas. This form of corrosion tends to attack the material rapidly, resulting in considerable material strength loss in a short amount of time. [30]

Table 2 Continued

Figure 11: Exfoliation [47]

Exfoliation Corrosion – This is a severe case of intergranular corrosion in which the expanding corrosion products force the surface grains of the material to lift. Aluminum, a common aircraft structural material, is commonly attacked by this form of corrosion. [39]

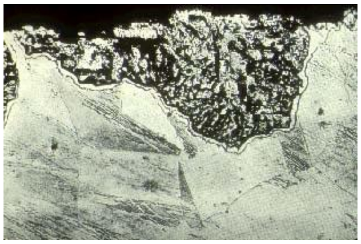


Figure 12: Dealloying [48]

Dealloying Corrosion – This form of corrosion, also referred to as selective leaching and dezincification, involves the removal of one element of an alloy. The material tends to look undamaged, however its strength is considerably reduced. [30]

Figure 13: Microbiological [49]

Microbiological Corrosion – Living organisms can be the cause of corrosion, since they can have an effect on the anodic and cathodic processes. This corrosion can easily be mistaken for pitting and thus correct diagnosis of the problem is essential. [30]

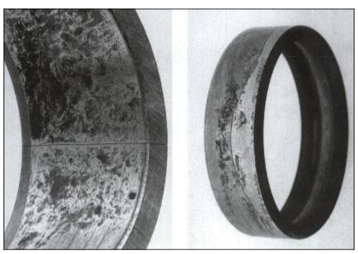


Figure 14: Fretting [50]

Fretting Corrosion – This corrosion results from two surfaces, under significant loads, that grind against each other. The grinding of the two surfaces causes the protective coatings to be scrapped away, leaving the metal exposed to corrosive environments. [9]

Figure 15: SCC [51]

Stress Corrosion Cracking – This form of corrosion is thought of as one of the most dangerous, since it can lead to unforeseen failure. Once corrosion weakens the material, it is vulnerable to the formation of a crack. The danger with this corrosion is the difficulty in detection. [30]

Table 2 Continued

Figure 16: Fatigue [52]

Corrosion Fatigue – Many components are under cyclic stress and their life is given by the number of cycles they can withstand. This number is greatly reduced in the presence of corrosion, causing the component to fail earlier than designed. [9]

Figure 17: Erosion [53]

Erosion Corrosion – This corrosion begins with mechanical forces initiating the erosion process. The elements that contributed to erosion can also instigate corrosion of a metal [30]. Erosion corrosion results in pits that indicate the direction of the erosion [9].

Figure 18: Hydrogen [54]

Hydrogen Embrittlement – Also known as hydrogen induced cracking (HIC), this form of corrosion is the result of atomic hydrogen seeping into a metal. This causes the material to lose some of its mechanical properties such as ductility and strength. [9]

Figure 19: Concentration Cell [55]

Concentration Cell Corrosion – This type of corrosion forms as the result of different areas on the surface of a component being exposed to varying strengths, or concentrations, of the same electrolytic solution. [31]

Figure 20: Cavitation [56]

Cavitation Corrosion – This type of erosion-corrosion occurs as a result of vapor bubbles residing near the metal that form and then collapse. The change of the flow direction is what causes the corrosion to eat away at the material. [9]

Table 2 Continued

Figure 21: High Temperature [57]

High Temperature Corrosion – Also known as dry corrosion, this type of corrosion forms without an electrolyte. Due to the high temperature environment, the rate of the corrosive oxidation reduction reaction is accelerated. This is a common problem in the aerospace industry. [40]

Figure 22: Crevice [45]

Crevice Corrosion – This type of corrosion tends to gravitate toward small cracks or crevices in the material, whether as the result of localized damage or manufacturing defects in the material. Only a small amount of electrolyte is needed to start the reaction. [30]

Developing a successful corrosion monitoring system involves overcoming the complexity of corrosion. Because there are so many types of corrosion, no one detection technique will provide a complete picture of structural health. In addition, one type of corrosion may instigate the formation of another different type of corrosion. To make matters worse, not all corrosion shows at the surface, and many aircraft parts are constructed in layers, making damage nearly impossible to detect visually. Finding hidden corrosion damage is further complicated by the fact that large sections of the aircraft are virtually inaccessible. As a result, portions of the aircraft must be painstakingly disassembled in order to access those areas.

The fact that there are so many variations of corrosion poses a challenge to developing a monitoring system, as there is no one detection technique that covers every single corrosion type [9]. It would not be practical or cost effective to monitor for each type of corrosion. Instead, a reasonable compromise must be made so that the system monitors what is needed.

2.4 Summary

Corrosion is the result of an electrochemical reaction between the aircraft structure and the atmosphere. The four essentials of corrosion formation are the presence of an anode, cathode, electrolyte, and metallic path. There are many factors that influence corrosion formation and severity, but perhaps the most influential factor is the atmosphere. Conditions such as temperature, humidity, and airborne contaminants have been directly linked to corrosion rate in many studies. However, despite numerous studies, corrosion still remains a highly unpredictable phenomenon. Corrosion has many variations and will form at any location with the right conditions. To add complication, corrosion often couples with other forms of failure such as fatigue, to further facilitate component failure.

Developing a successful corrosion monitoring system will involve balancing the technical challenges that are involved, as well as the cost and effectiveness of the system. It would not be practical to monitor for each type of corrosion, so a reasonable compromise must be made to provide what information is needed, while keeping the system feasible.

The structural evaluation of the UH-1 fleet will attempt to answer the questions of what method is appropriate for analyzing maintenance information. The answer to this question will be the key in designing a corrosion monitoring system that targets the most affected areas of the aircraft.

CHAPTER 3: STRUCTURAL EVALUATION

3.1 Overview

The first task in this investigation was to perform a structural evaluation of the UH-1 fleet. The structural evaluation of the UH-1 fleet included the analysis of six years of intermediate-level aircraft maintenance data. The objective was to locate corrosion problem areas on the UH-1 aircraft and investigate potential correlation between corrosion damage and aircraft operating location. To accomplish this objective, the structural evaluation process was broken down into six steps. The first three steps involved analyzing maintenance information in order to identify problem areas and prepare the data for modeling. The second three steps consisted of building a prediction model and evaluating it for usability.

1. Gather maintenance information
2. Convert to numerical data
3. Identify problem areas
4. Test for relationships
5. Build prediction model
6. Evaluate model

3.2 Gather Maintenance Information

The first step in the structural evaluation was to gather maintenance information. Six years of Air Force UH-1 aircraft maintenance data [33] was used for this investigation. The timeline analyzed was from January 2004 through February 2010, representing a total of 115,394 operating hours. The data consisted of field-level maintenance actions performed as a result of corrosion, whether it was part repair or replacement. Maintenance information was gathered by downloading maintenance actions for various work unit codes (WUC).

Work unit codes are used to represent the systems on the aircraft, from airframe to avionics. Each work unit code corresponds to a unique set of items. Due to the time involved in data mining, the number of WUCs used in this investigation was kept to a minimum. Three work unit codes, shown in Table 3, were chosen for this investigation. These codes were selected since they represent major structural systems, and thus would encompass the majority of the aircraft corrosion damage.

Table 3: Major Structural Systems

WUC	Description
11000	Airframe Systems
22000	Turboshaft Propulsion Systems
26000	Rotary Drive Systems

Table 4 shows an example of aircraft maintenance data. Note that this is purely a fictitious example. Of interest to this investigation were the location, discrepancies, corrective actions, labor man hours (LMH) required to resolve the issue, and the work unit code. Note that maintenance data was only gathered for the UH-1N aircraft. This was due to the fact that data on the other UH-1 variants was not easily accessible. The structural differences between the UH-1N and UH-1H/V aircraft are minor, thus data gathered on the UH-1N aircraft was considered sufficient to be representative of the entire UH-1 fleet.

Table 4: Sample Data

WUC	NOUN	TAIL	BASE	START	STOP	LMH	UP	CT	CS	WD	TM	HM	AT	JCN	WCE	DISCREPANCY	CORRECTIVE ACTION
11000	Floor	1123	XYZ AFB	1/11/2010	1/11/2010	3.0	1	1	2	F	A	70	F	123456780	1	corrosion under cabin floor	Infected area repaired and painted
11ABC	Pylon Support	1111	XYZ AFB	2/1/2010	2/2/2010	7.5	1	1	4	M	B	190	Q	125478912	1	corrosion found on transmission pylon	pylon flange replaced
11BCD	Panel	1345	XYZ AFB	2/1/2010	2/1/2010	3.4	1	1	3	H	H	804	S	251648794	2	corrosion found on honeycomb panel	panel repaired ad coated with cpc
26FAD	Engine	1231	XYZ AFB	2/23/2010	2/30/2010	45.0	1	1	2	B	P	799	V	213459871	1	fatigue crack and corrosion on service deck	crack repaired, corrosion damage area sanded and repainted
22AAA	Support	1123	XYZ AFB	5/21/2010	5/23/2010	32.0	1	1	4	Q	R	255	B	245156874	1	Bearing hangar support fitting cracked and has corrosion damage	support fitting replaced

It was often the case that one action was entered into the maintenance database multiple times. It was necessary to eliminate repetitious entries, since the number of actions was important to the modeling task. To consolidate the actions, labor man hours were summed together, and one line in the database was used to represent one job control number (JCN). After consolidation, a total of 174 maintenance actions were left to be converted into numerical data.

3.3 Convert to Numerical Data

What method is appropriate for analyzing maintenance information? To answer this question, it was imperative to convert the information downloaded from the maintenance database into analyzable data. In order for the maintenance information to be plotted and compared, the location and discrepancy information needed to be converted into numerical data. The following are descriptions of each variable used in the conversion process.

3.3.1 Time of Wetness

Since the majority of aircraft life is spent on the ground, it is the atmosphere at its assigned base that is most influential for the growth of corrosion. If the aircraft are flown an average of 300 hours a year, then the aircraft spends roughly 3% of its life exposed to corrosive conditions that are different from the conditions at the base. For this reason, it was assumed that it is the base atmosphere that is responsible for aircraft corrosion. Therefore, the effects of the individual aircraft missions on corrosion were not considered.

Temperature and humidity are well known factors in atmospheric corrosion. To capture this information, hourly weather information [13] was examined for each location for the duration of one year. The variable time of wetness (TOW) was chosen to capture the amount of exposure of the structure surface to conditions that are favorable to corrosion. It represents the number of hours per year in which the temperature is above freezing (32°F) and the relative humidity is above 80% [30].

Frequency of precipitation, fog, dew, and melting snow, can also be included in a TOW variable [30]. While rain and other precipitation may be thought of as a good indicator of corrosion, including this as a variable may be misleading. Some aircraft spend more time in the hangar than others. Thus, to eliminate possible error, corrosion damage to the outer skin was not considered. In addition, the load bearing aircraft structure is mostly contained on the inside of the aircraft, protected from rain and snow. Aircraft structure corrosion would then be primarily influenced by temperature and humidity, which are already incorporated in the TOW indicator.

3.3.2 Sulfur Dioxide Emissions

Airborne impurities are another important factor in corrosion damage. Pollutants tend to accelerate the rate of corrosive activity, and can form an electrolyte solution on the surface during the time of wetness. Sulfur Dioxide (SO_2), considered one of the most important corrosive pollutants, was taken into account by examining emissions data for each aircraft location. Since pollution concentration tends to decrease with distance from the source, only emissions (in tons per year) for each aircraft location was considered. SO_2 emissions for each location were totaled and divided by the area occupied by the base, in square miles. Table 5 shows a summary of the atmospheric conditions for each aircraft location.

Table 5: Climate Statistics

TOW	SO2 (Tons/year/sq. mi)
2814	0.6711
3896	2.7157
2358	0.0277
758	0.0000
608	0.0000
842	5.6202
1962	0.0001
2776	2.7157
3896	0.0000

3.3.3 Damage Area

Next, information given by the work unit code, noun, and discrepancy was used to identify which section of the aircraft that was damaged. The area was identified with a number from 1 to 7, as shown in Figure 23.

Area 1 included the nose area, forward of crew doors. Areas 2 and 3 included the forward fuselage. Area 4 was the pylon area, which included the main rotor, transmission, and drive shaft. Area 5 encompassed the engine, and Area 6 included the entire tail boom. Areas 1 through 6 represented aircraft structure and were found in the UH-1 maintenance manuals. Area 7 was added to provide a category for electrical components. Since the focus of this study was on structural integrity of the aircraft, electrical component corrosion was separated from the other categories.

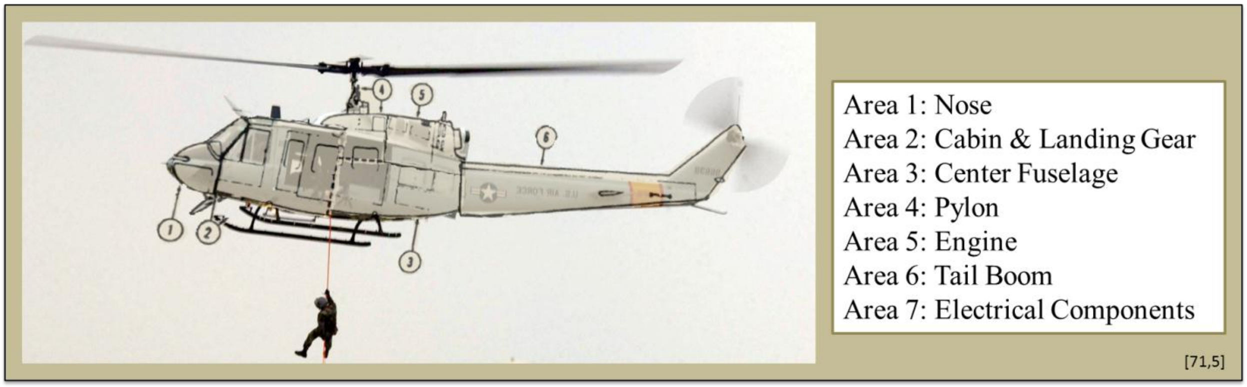


Figure 23: Aircraft Damage Areas

3.3.4 Corrective Action

Lastly, the corrective action was converted to either a "1" or a "2", depending on whether the component was repaired or replaced. If the component was repaired, a "1" was used. If the component was replaced, a "2" was used. Occasionally there were actions in which the component was neither repaired nor replaced. In these instances, a category of 1 (for repair) was used; due to the fact that labor man hours were spent investigating the problem.

Table 6 shows an example of how the maintenance information was converted into numeric data. Note that this is a fictitious example. As shown in the table, all information was replaced with quantitative data.

Table 6: Example Numerical Data

TOW	SO2 Emissions (Tons/year)	Damage Area	Corrective Action
2814	2.7	2	1
608	1.6	3	2
1125	0.01	3	1
742	0.5	5	1
2654	2.7	3	2

The information was then compressed, such that one data point represented one location, or climate condition. The compression was performed by taking the total number of incidences and dividing by the total number of aircraft for that location and dividing by the time period, or three years. In the case of LMH, the total number of hours spent by each location was divided by the number of aircraft and the time period. For mean time to repair (MTTR), the total number of LMH spent at each location was divided by the number of maintenance actions for that location. The final sample data is shown in Table 7.

Table 7: Finalized Data for Model Creation

TOW	SO2 (Tons/Year/sq. mi)	Repairs (/Aircraft/Year)	Replacements (/Aircraft/Year)	LMH (/Aircraft/Year)	Actions (/Aircraft/Year)	MTTR
2814	0.6711	0.254	0.079	0.642	0.333	1.926
3896	2.7157	0.500	1.000	10.250	1.500	6.833
758	0.0000	0.056	0.444	1.124	0.500	2.248
608	0.0000	0.111	0.083	0.622	0.194	3.200
2358	0.0277	0.167	0.333	5.117	0.500	10.23
3896	0.6711	0.000	1.250	2.983	1.250	2.387
842	5.6202	0.021	0.104	0.219	0.125	1.750
1962	0.0001	0.000	0.500	2.877	0.500	5.754
2776	2.7157	0.708	0.417	1.713	1.125	1.522

3.4 Identify Problem Areas

Before a prediction model could be created, it was important to take a step back and understand what areas of the UH-1 aircraft have the most problems with corrosion. To accomplish this, data for each damage area and corrective action were gathered and summarized for comparison. The main categories of comparison were repairs and replacements. Data was compared both in terms of both mean time to repair and number of occurrences.

The first comparison was the number of occurrences. Figure 24 shows how repairs and replacements contributed to the total number of corrective actions. Repairs came to 37% of the total actions, while replacements represented 63% of actions. Components that were not too damaged by corrosion were cleaned and placed back on the aircraft. This included both small components, such as rivets, nuts, and bolts, as well as larger structural components, such as drive shafts and frames. Parts that were too damaged were replaced. As shown in the figure, replacements occurred nearly twice as often as repairs.

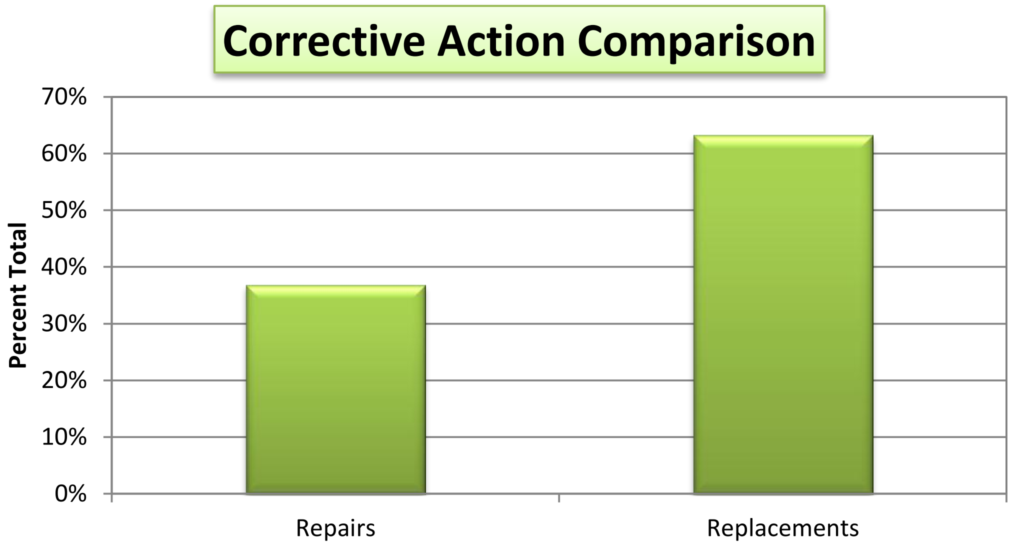


Figure 24: Corrective Action Comparison

For both repairs and replacements, the majority of actions were for smaller components, such as fairings, bolts, nuts, rivets, screws, and electrical connectors. This was to be expected, as corrosion tends to be more damaging where two components come together, where there are small gaps and crevices for corrosive products to form. These were also locations at which dissimilar metals may be joined, spurring corrosion formation.

A comparison of the mean time to repair for corrective actions is shown in Figure 25. MTTR represented the average amount of time required to make a repair. Since this study involved comparing maintenance labor time for different actions, MTTR was also used to compare the average time to make a replacement. To calculate the MTTR for "Repairs", the total LMH for repairs was divided by the number of repair actions. The same procedure was used to calculate MTTR for replacements. The plot shows that the average amount of time used to make repairs was approximately 2 hours, while the average time for replacements was over twice that, at roughly 4.5 hours. This was due to the fact that replacing larger structural components, such as drive shafts and frames, consumed far more time than cleaning corrosion byproducts from the surface.

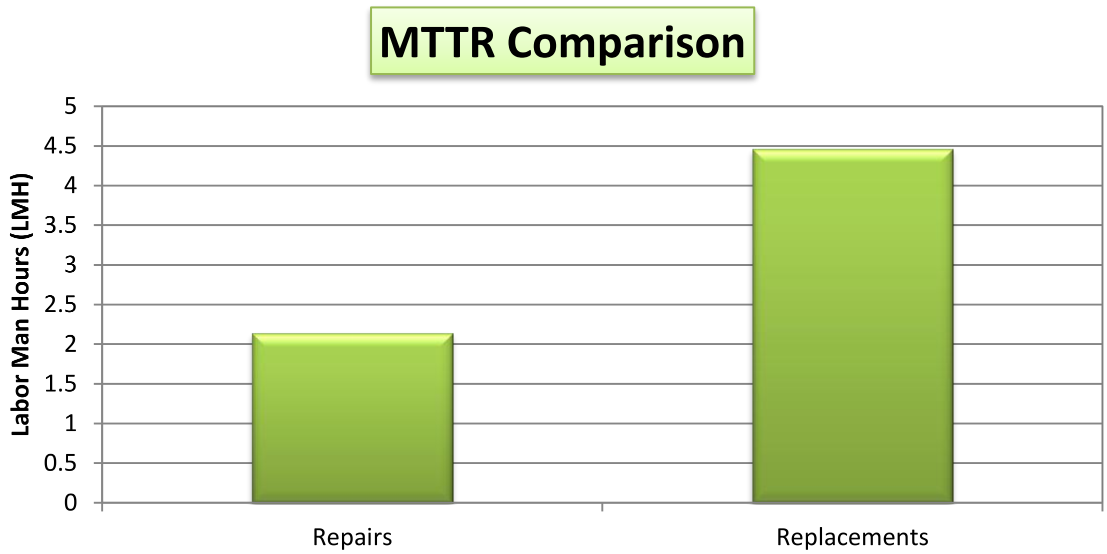


Figure 25: Corrective Action MTTR Comparison

Replacements not only occurred twice as often, but took twice as long to finish. This indicated that replacements were the main driver in maintenance cost and effort. Monitoring corrosion damage will assist in reducing part replacements, allowing for the components to be cleaned and treated before the damage is so great that a replacement is necessary.

Similar to previous studies, a total count of occurrences was found for each aircraft area. Figure 26 shows the percent of total actions for each area, in a ranked order from highest to lowest. The curve shows the cumulative percent for each additional damage area that is included from left to right. The arrow shows where the curve reaches 80%, showing that the first four damage areas represented 80% of maintenance actions.

The engine area ranked the worst, carrying 24% of the total maintenance actions. This was expected, based on the fact that engine emissions tend to be very corrosive to the nearby structure. Frequent problems included panels, ducts, screens, and mounting structure. The tail boom ranked second, accounting for 22% of the actions. Corrosion problems with the tail rotor drive shaft and 42 degree gear box contributed to the majority of the maintenance actions for this area of the aircraft. The third worst area was the cabin and landing gear area, with 21% of maintenance actions. Floor panels and door components were the most affected by corrosion in this area of the aircraft. Corrosion damage to the pylon structure represented 12% of maintenance actions. In total, these four areas accumulated approximately 80% of corrosion problems.

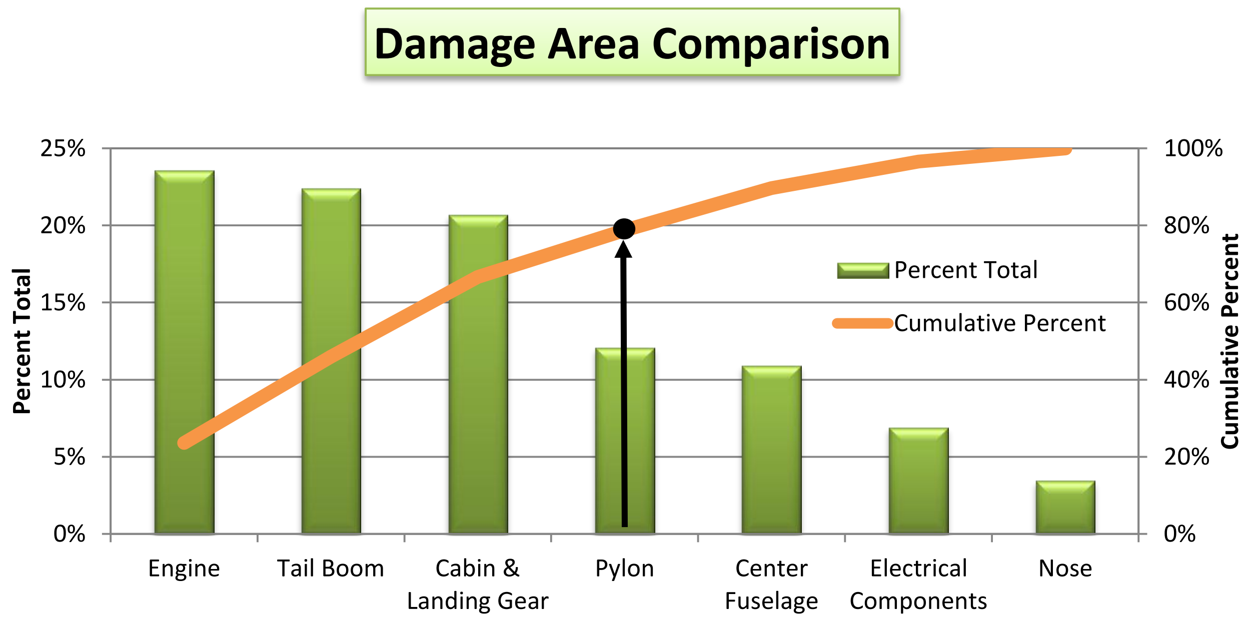


Figure 26: Damage Area Comparison

Although it was important to understand where the majority of the maintenance actions happen, it was also important to understand where time was being spent on performing those actions. Figure 27 describes the average repair time, in hours, for each aircraft area. The center fuselage took the lead with an average of 4.5 hours per maintenance action. Corrosion on the cabin floor tended to drive up repair time. Note that this area was only responsible for 11% of maintenance actions, however, it was still problematic due to the amount of time needed to correct the problems. The engine and tail boom area were nearly the same, with approximately 4 hours per action. Not only were the engine and tail boom areas time consuming, they were also most frequently in need of repair.

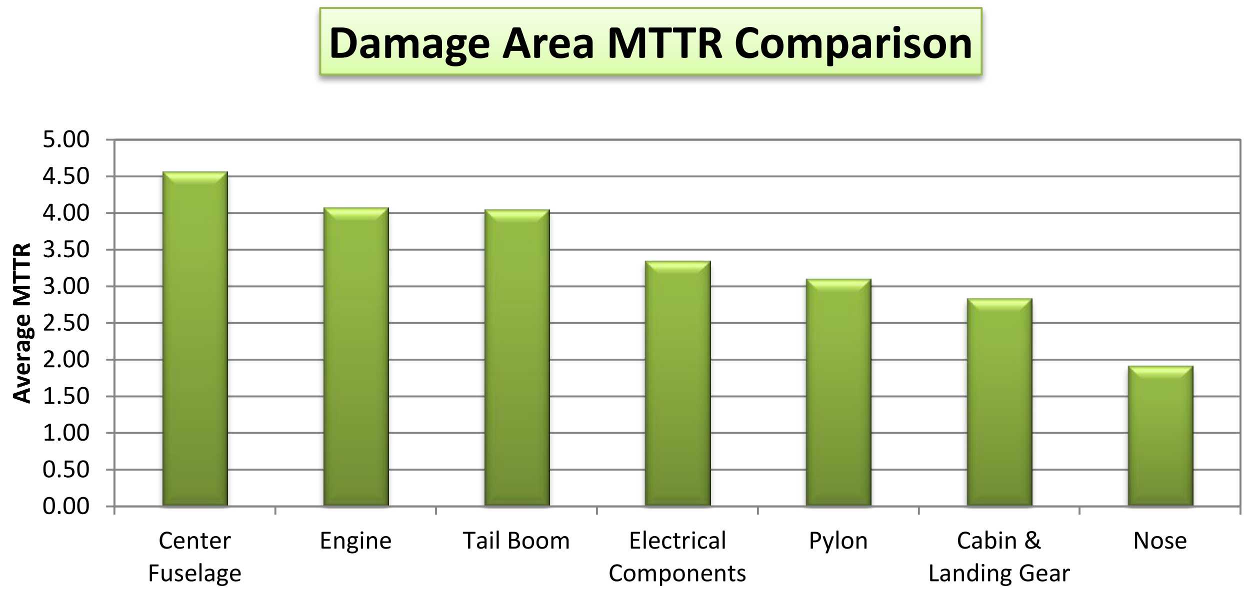


Figure 27: Damage Area MTTR Comparison

By comparing maintenance actions and time for each aircraft area, the most problematic areas of the aircraft were found. The cabin & landing gear, engine, and tail boom were the three most problematic areas in terms of frequency. The center fuselage, engine, and tail boom were the most costly in terms of maintenance time. These areas were important considerations for sensor placement. With sensors in place, data can be gathered and the reasons why the areas are so frequently corroding can be investigated. In addition, sensors can be placed in hard-to-reach areas of the aircraft and in time, possibly reduce the number of inspections that must take place in those areas.

3.5 Test for Relationships

Does the location of aircraft operation have an impact on corrosion damage? In order to answer this research question, a model must be fit to the maintenance data. To empirically fit a model to data, a regression technique was used. Regression analysis is often referred to as response surface methodology and is composed of linear and non-linear regression. Once a modeling method was chosen, a significance test was used to evaluate relationships among the variables of influence and metrics of interest. Results from the significance test would dictate whether a model could be created.

3.5.1 Model Selection

Figure 28 shows the method down-selection as red arrows. A linear regression model was chosen as it is the simplest model and generally works for real world problems. A multivariate model was used, since maintenance data has many parameters. Lastly, the model should be second-order, as this type of model is effective for most real problems [21].

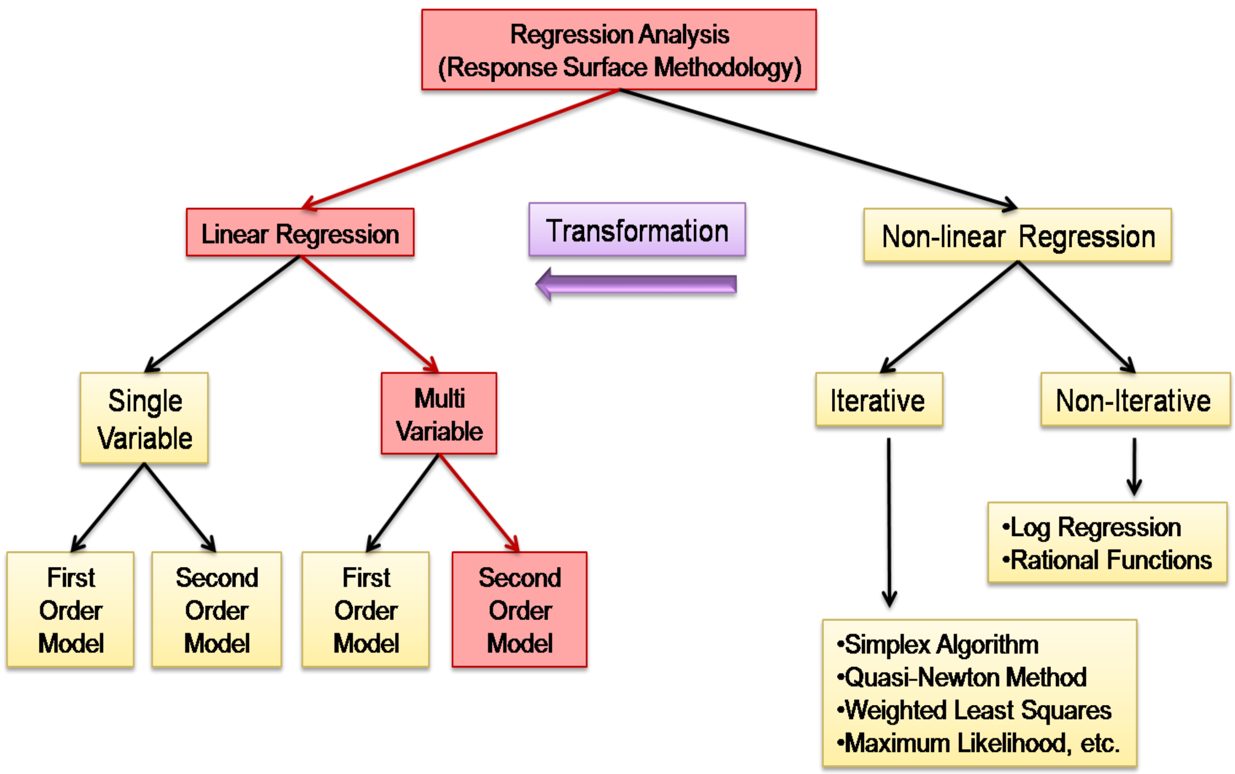


Figure 28: Method Down-selection

The formula for a second order model is shown in Figure 29. The model is composed of the response (η), regressors (x_j), and regression coefficients (β). The response is the dependent variable, and the metric of interest. Regressors are the independent variables and may be quantitative or qualitative. Regression coefficients are the unknowns and are found via the least squares method, in which a model is fit while minimizing the sum of the squares of the residual errors. Using a second order model is advantageous, since a large variety of functions is encompassed by the model, estimating the regression coefficients is simple (using method of least squares), and the model tends to work well for real problems. [21]

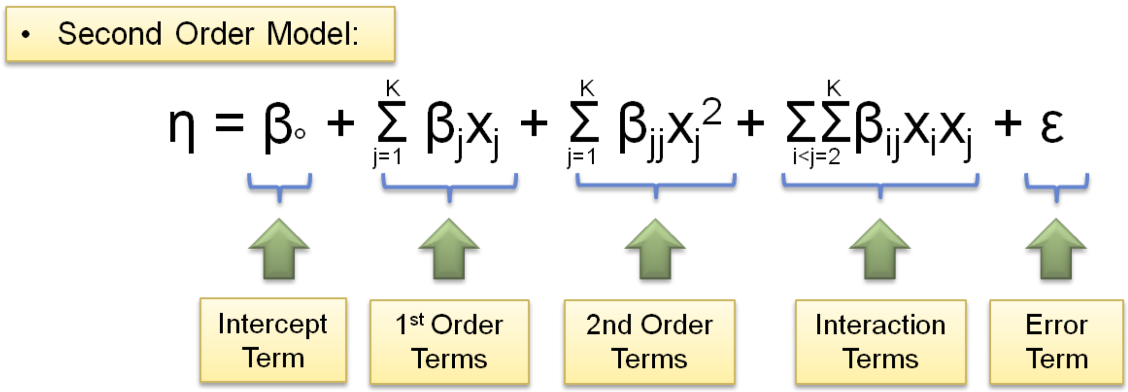


Figure 29: Second Order Model Equation [21]

Once the maintenance information was converted to numerical data, it was analyzed using JMP® 8 software from SAS. It is statistical software that is highly interactive, allowing for visual representation of data and results [16]. In order to analyze the data, it was necessary to answer the next research question. What are the metrics of interest and variables of influence?

Variables of influence were chosen based on their significant impact on corrosion growth and included TOW and SO_2 emissions. Responses of interest, shown in Table 8, were chosen based on their impact with aircraft availability and maintenance cost. These included mean time to repair, labor man hours, number of part replacements, and number of part repairs.

Table 8: Regressors and Responses of Interest

Regressors	Responses
Time of Wetness (TOW)	Repairs/Aircraft/Year
SO2 (Tons/year/sq. mi)	Replacements/Aircraft/Year
	LMH/Aircraft/Year
	MTTR

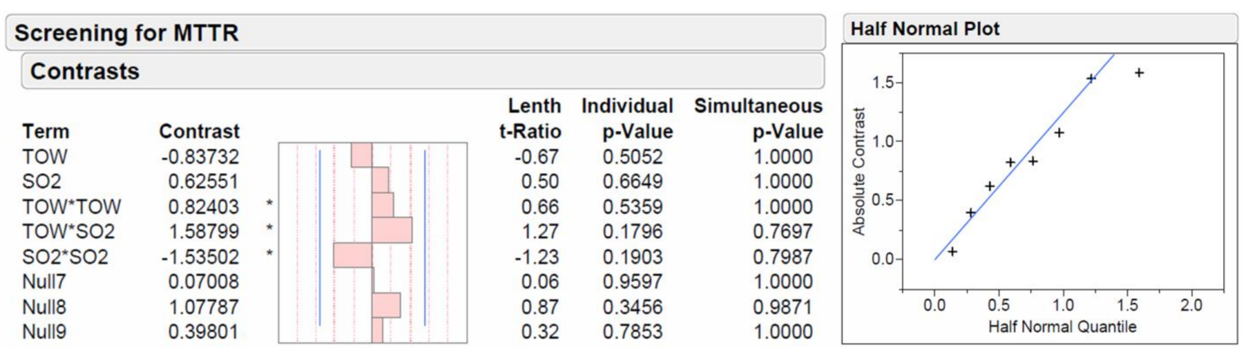
The responses provide information on the number of maintenance actions as well as the time required to deal with aircraft corrosion issues. If the model is developed successfully, corrosion damage can be predicted for any number of aircraft and any time span.

3.5.2 Screening Analysis

A screening test was used to identify regressors that were significant to the responses listed in Table 8. The test first identified main effects, which were TOW, TOW*TOW, SO_2 and SO_2*SO_2. Second order interactions were tested next, and included TOW*SO_2. The process continued until the number of effects analyzed was equal to the number of rows of data. This study consisted of nine rows of data, but only two regressors. In order for the software to reach nine effects, it created random orthogonalized effects to account for the remaining variation, labeled as "Null". Effects that were not automatically orthogonal were forced orthogonal and were shown with an asterisk. [3]

The screening test for mean time to repair, or MTTR, is shown in Figure 30. The bar chart shows the p-Value of each effect. Since this was a second order evaluation, squared and interaction effects were included in the test. For an effect to be significant, its p-Value needed to be less than 0.1, and the corresponding bar on the bar chart would cross over the vertical blue line.

The half normal plot shows the effects against the normal quantiles of the normal distribution. Standard error is represented by the blue line. For a variable to be significant, it needed to dramatically deviate from this line. As shown in the figure, none of the regressors were found to be significant for the MTTR response.


Screening for MTTR
Contrasts

Term	Contrast		Lenth t-Ratio	Individual p-Value	Simultaneous p-Value
TOW	-0.83732		-0.67	0.5052	1.0000
SO2	0.62551		0.50	0.6649	1.0000
TOW*TOW	0.82403	*	0.66	0.5359	1.0000
TOW*SO2	1.58799	*	1.27	0.1796	0.7697
SO2*SO2	-1.53502	*	-1.23	0.1903	0.7987
Null7	0.07008		0.06	0.9597	1.0000
Null8	1.07787		0.87	0.3456	0.9871
Null9	0.39801		0.32	0.7853	1.0000

Figure 30: MTTR Screening Test

The screening test for Repairs/Aircraft/Year is shown in Figure 31. For this regressor, only an interaction effect, SO_2*TOW, was shown to be significant. Figure 32 shows the results of the screening test for

Replacements/Aircraft/Year. Two effects, SO2 and SO2*SO2, were revealed as significant. Figure 33 shows the last test, LMH/Aircraft/Year. SO2, SO2*TOW, and TOW*TOW passed the significance test.

Screening for Repairs

Contrasts

Term	Contrast		Lenth t-Ratio	Individual p-Value	Simultaneous p-Value
SO2	0.104564		1.16	0.2126	0.8480
TOW	0.065104		0.72	0.4412	0.9999
SO2*SO2	-0.055842	*	-0.62	0.5688	1.0000
SO2*TOW	0.173357	*	1.93	0.0705	0.3563
TOW*TOW	-0.063976	*	-0.71	0.4534	1.0000
Null7	-0.017289		-0.19	0.8708	1.0000
Null8	0.020993		0.23	0.8423	1.0000
Null9	-0.040448		-0.45	0.6995	1.0000

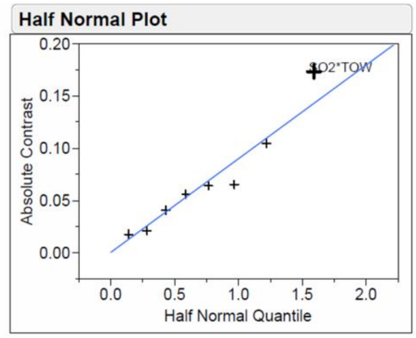


Figure 31: Repair Screening Test

Screening for Replace

Contrasts

Term	Contrast		Lenth t-Ratio	Individual p-Value	Simultaneous p-Value
SO2	0.283977		3.10	0.0248*	0.1363
TOW	-0.028190		-0.31	0.7815	1.0000
SO2*SO2	0.180629	*	1.97	0.0621	0.3348
SO2*TOW	-0.021226	*	-0.23	0.8384	1.0000
TOW*TOW	0.061049	*	0.67	0.5002	1.0000
Null7	-0.002426		-0.03	0.9821	1.0000
Null8	-0.081221		-0.89	0.3203	0.9830
Null9	-0.158114		-1.73	0.0875	0.4569

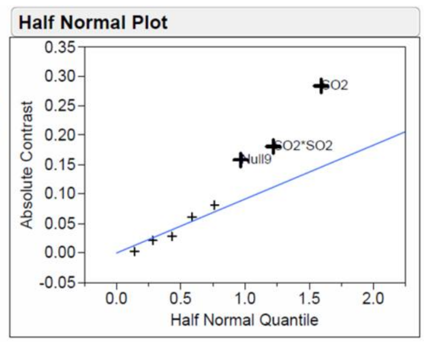


Figure 32: Replacement Screening Test

Although some significant effects were identified in the screening analysis, this may not be enough to create a reliable model. A good model requires strong correlations among the variables and responses. Without strong correlation, the model would not be a reliable tool for predicting corrosion damage to aircraft.

Screening for LMH

Contrasts

Term	Contrast		Lenth t-Ratio	Individual p-Value	Simultaneous p-Value
SO2	1.91625		4.24	0.0141*	0.0737
TOW	0.06846		0.15	0.8972	1.0000
SO2*SO2	0.55343	*	1.23	0.1980	0.8104
SO2*TOW	1.07374	*	2.38	0.0429*	0.2053
TOW*TOW	1.90704	*	4.22	0.0143*	0.0747
Null7	-0.43891		-0.97	0.2864	0.9546
Null8	-0.16340		-0.36	0.7600	1.0000
Null9	0.04823		0.11	0.9280	1.0000

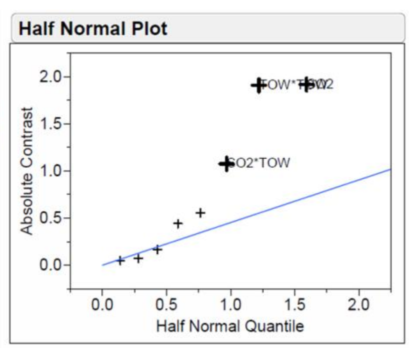


Figure 33: LMH Screening Test

The lack of significance among the effects suggests that there were additional factors that were affecting the data that were not accounted for. Although previous studies used both TOW and SO_2 as regressors, corrosion data was gathered using test coupons that were placed at each location. This method provided accurate data for model creation, since values for TOW and SO_2 were obtained by measuring at each location. In this investigation, historical weather data and Environmental Protection Agency emissions data was used to find TOW and SO_2, which is not as reliable as measuring the atmospheric conditions at the test location directly. In addition, coupons provide a simple method of directly measuring material loss from corrosion. Analyzing maintenance data was a far more indirect method of correlating corrosion damage to atmospheric conditions.

3.6 Build Prediction Model

Results from the screening analysis were used to create models relating the variables to the responses of interest. As shown by the screening test, MTTR did not correlate well with any of the variables, and was not modeled. Repairs, Replacements, and LMH responses were modeled using the effects that were selected as being significant by the screening analysis. It is important to note that if an interaction was determined to be significant, the corresponding main effects were added to the model, regardless of whether they were or were not significant.

Table 9 shows the prediction expressions that were developed for each of the responses, with the exception of MTTR. Recall that the units of the responses are per aircraft per year.

Table 9: Prediction Expressions

Response	Prediction Expression
Repairs	-0.09243 + 6.5470x10-5 * SO_2 + 8.6291x10-5 * (SO_2 – 2212.2222) * (TOW-1.3801) + 0.1087 * TOW
Replacements	-0.2659 + 2.3450x10-4 * SO_2 + 1.4887x10-7 * (SO_2 – 2212.2222) * (SO_2 – 2212.2222)
LMH	-11.0548 + 4.8099x10-3 * SO_2 + 0.002511 * (SO_2 – 2212.2222) * (TOW – 1.3802) + 1.9708 * (TOW – 1.3802) * (TOW – 1.3802)

3.7 Evaluate Prediction Model

Once the prediction expressions were developed, the models were evaluated. In this section, each model was evaluated separately, and recommendations were made as to its usability. Several items were used to judge the goodness of fit of the models, including R^2 values, actual by predicted plots, residual plots, and model fit error (MFE).

The R^2 value is a value from 0 to 1 and represents the closeness in which the response is related to the regressor. Sample values of R^2 are shown in Figure 34. In general, values of R^2 greater than 0.8 are acceptable. The charts show how correlation between the model and the data improves as the R^2 value increases.

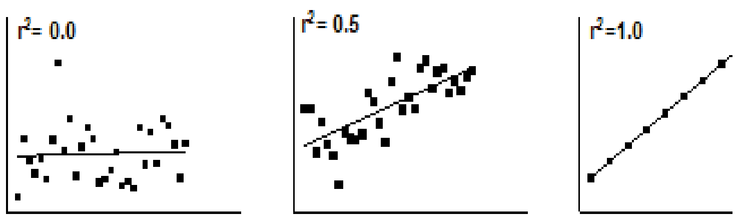


Figure 34: Sample R Squared Values [38]

The actual by predicted plot displays the actual response values against the response values predicted by the model. An example is shown in Figure 35. It is best to have a nearly forty five degree line, with data evenly distributed as shown in the figure. The red dotted lines denote 95% confidence intervals, which should be narrow and cross over the mean line, shown in dotted blue.

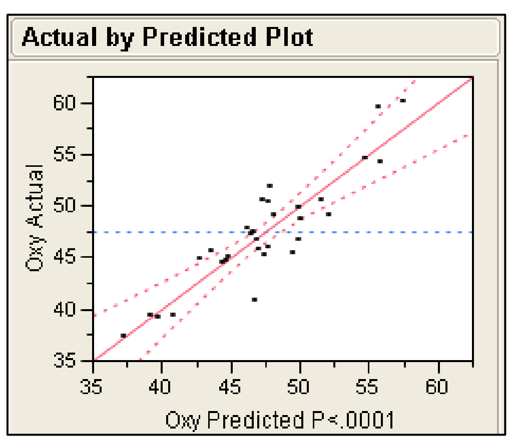


Figure 35: Sample Actual by Predicted Plot [3]

The residual by predicted plot, displayed in Figure 35, shows the error for each value that was predicted by the model. For this indicator, a random pattern of data and a small range on the residual axis indicates good model fit. Ideally, the total range of the residual axis should be roughly 10% of the predicted value range.

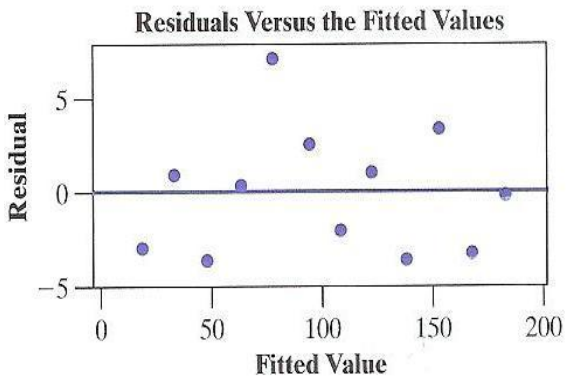


Figure 36: Sample Residual by Predicted Plot [33]

The final indicator, MFE, shows how well the model fits the points that were used to create it. MFE is evaluated by comparing the distribution of the residual errors to a normal distribution. A model with good fit will have a distribution with a mean close to zero and a standard deviation less than one.

3.7.1 Repairs Model

Figure 37 shows various data and plots used to describe the goodness of fit for the Repairs model. The Summary of Fit table shows an R^2 "RSquare" value of 0.69. This value was low, suggesting a low correlation between the data and the model. The actual by predicted plot shows very wide confidence intervals and significant data scatter, another indicator of an inadequate model. The residual by predicted plot shows an uneven scatter of points, an indication that there were other effects present that have not been accounted for in this model.

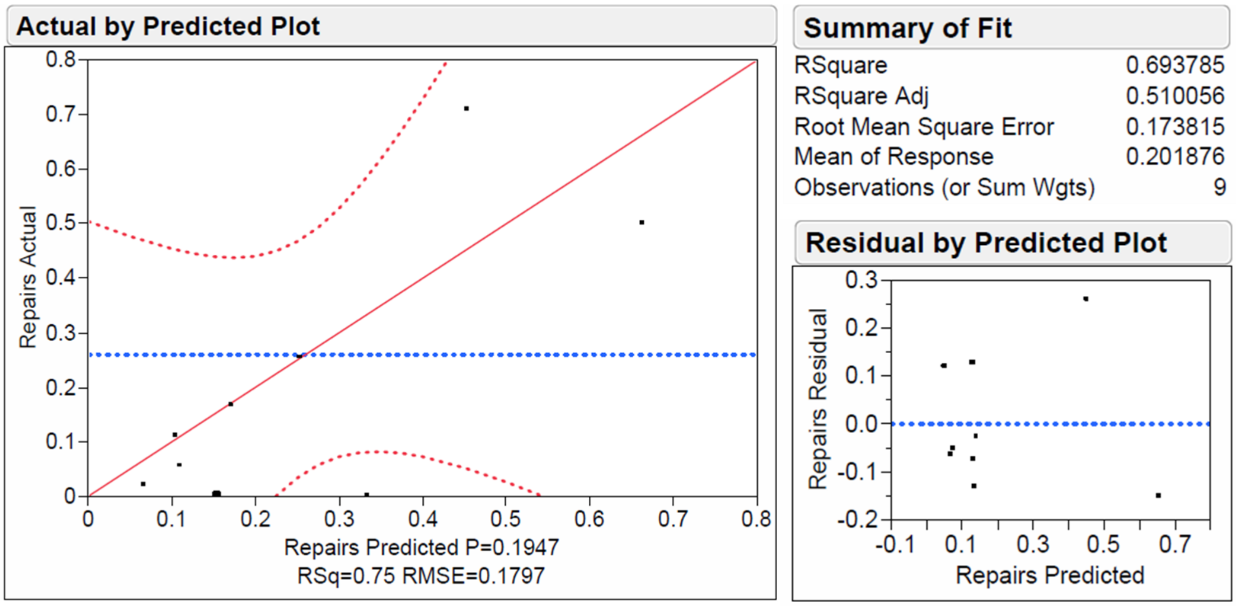


Figure 37: Repairs Model Evaluation

Figure 38 shows the residual error distribution for the Repairs model. While the mean was approximately equal to zero and the standard deviation is less than one, this distribution remained less than desirable. The gaps in the distribution plot could be attributed to the few data points used to create the model. The range of the error was on the same order as the actual data points, pointing to large errors in the model predictions. With this evidence, it was easy to conclude that this particular model is unsuitable.

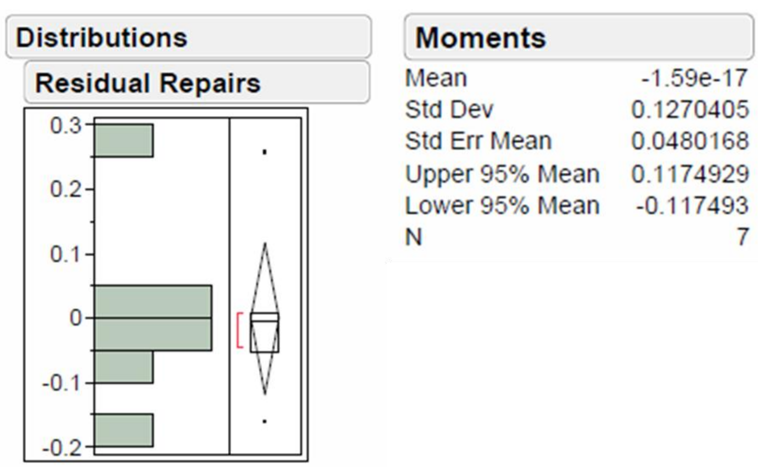


Figure 38: Repair Model Residual Distribution

3.7.2 Replacements Model

Figure 39 shows the goodness of fit evaluation for the Replacements model. For this model, the R^2 value was also less than 0.8, suggesting not enough correlation with the data. The actual by predicted plot shows a wide confidence interval. The data points tended to cluster on the left side of the plot, while there were two other points grouped on the right side of the plot. Similar clustering was present in the residual by predicted plot. Clustering was an indication that higher order terms needed to be included in the model. With few data points, it was difficult to distinguish clustering from gaps caused by lack of data.

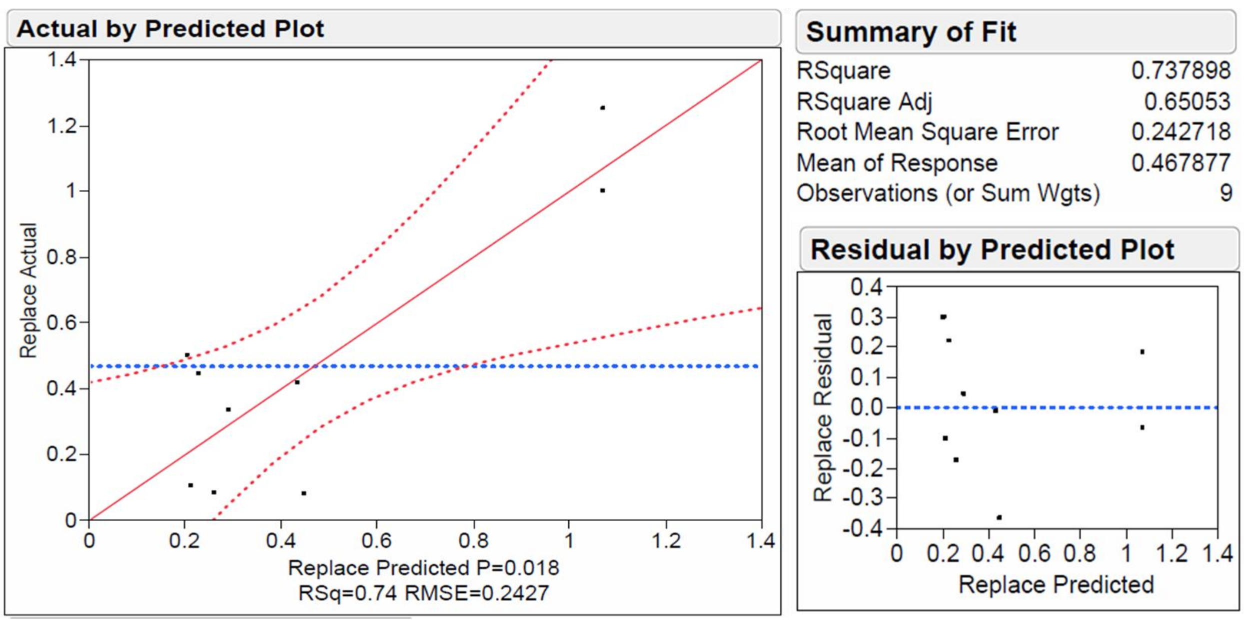


Figure 39: Replacements Model Evaluation

The residual error distribution is shown in Figure 40. The mean and standard deviation were acceptable, however, the distribution range was the same order as the data itself. This evaluation shows that the Replacements model will not be an effective tool in making predictions.

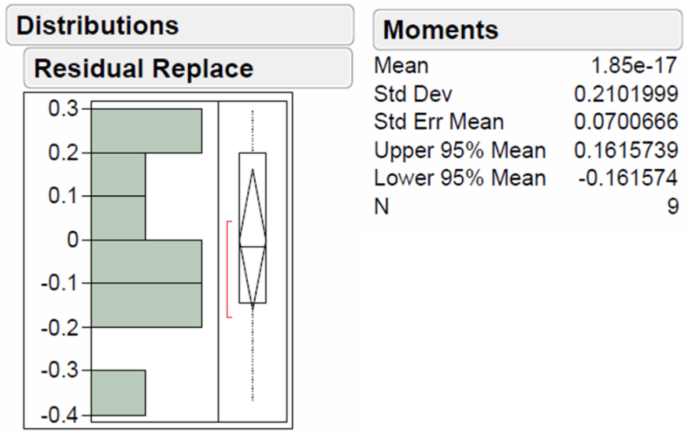


Figure 40: Replacements Model Residual Distribution

3.7.3 LMH Model

The model evaluation for LMH is shown in Figure 41. For this model, the R^2 value is below 0.8. The actual by predicted plot shows the data points were not well represented by the model. In addition, wide confidence intervals were also present, another indication of poor fit.

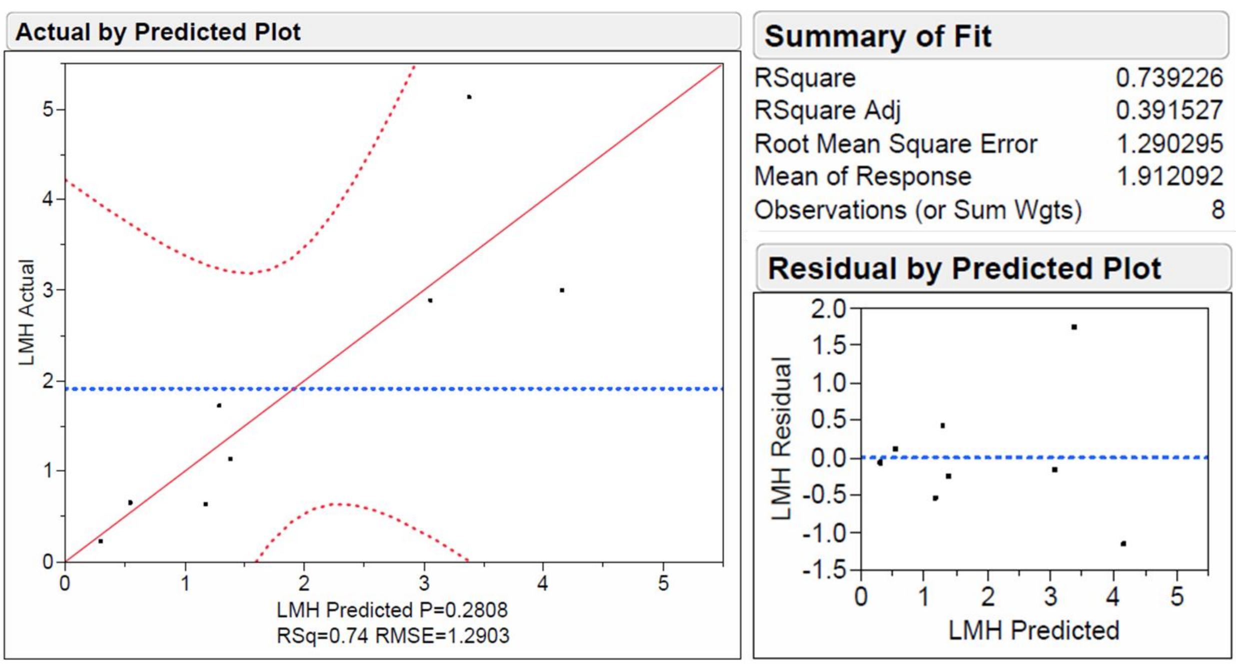
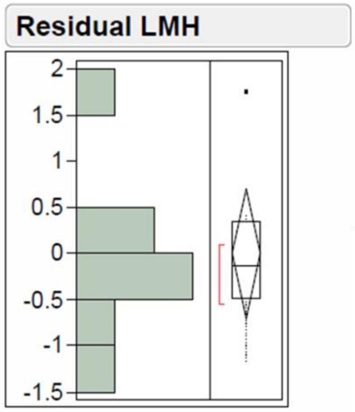


Figure 41: LMH Model Evaluation

The residual by predicted plot shows a random distribution of error, which was acceptable, however, the range of the error axis was the same as that of the data points. Figure 42 shows the residual distribution for the model. Although the mean and standard deviation were acceptable, the range of error was much too large. This model was also inadequate.



Moments

Mean	4.996e-16
Std Dev	0.8446964
Std Err Mean	0.2986453
Upper 95% Mean	0.7061839
Lower 95% Mean	-0.706184
N	8

Figure 42: LMH Model Residual Distribution

It was determined that the models created in this study did not accurately represent the gathered maintenance data. As a result, the impact of aircraft location on corrosion damage could not be determined. The models could not be used for representing corrosion damage to aircraft based on the atmospheric conditions of aircraft locations.

3.8 Findings

The system evaluation resulted in several findings regarding data mining of aircraft maintenance data that are as follows:

- Replacements occurred twice as often and took twice as long.
- Highly problematic areas included the engine, tail boom, center fuselage, and cabin.
- Maintenance data did not provide the level of accuracy needed for creating a reliable model.
    - Maintenance data was often ambiguous.
    - 174 actions were recorded.
    - 9 aircraft locations were analyzed.
    - Data was averaged by location.
    - Previous condition of the aircraft could not be determined.

- Aircraft usage could not be determined.

It was found during the analysis that replacements occurred twice as often and took twice as long to finish. Repairs came to 37% of the total actions, while replacements represented 63% of actions. The average amount of time used to make repairs was approximately 2 hours, while the average time for replacements was over twice that, at roughly 4.5 hours.

Highly problematic areas on the aircraft included the engine, tail boom, center fuselage, and cabin. These areas ranked the highest in terms of number of actions as well as mean time to repair. These areas will be the main focus for sensor placement, although all areas of the aircraft are important.

It was determined that the models created in this study did not accurately represent the gathered maintenance data. The models could not be used for predicting corrosion damage to aircraft based on the atmospheric conditions of aircraft locations. There were several limitations from the maintenance data as well as the analysis that were recognized as possible contributors.

One such limitation was the ambiguity of maintenance data. Data was mined based on the "how malfunctioned" (HM) codes that were used to classify the problem, "action taken" (AT) codes that classified the resolution, as well as the comments used to describe the issue. It was often the case that comments did not agree with the codes, creating confusion as to whether corrosion was the source of the problem. For example, an entry would include the HM code that indicated severe corrosion, however, the comments would suggest that the problem was an incorrect part number label.

The second limitation was the small number of maintenance actions that were gathered. Only 174 actions were found, which could be the result of several possibilities. The first possibility was that not all corrosion actions were being recorded. Only one HM code can be used to classify the problem, so if the part failed due to cracking but corrosion caused the cracking, the code would only reflect failure due to cracking. The comments may only state that the part was cracked and needed replacement, and not include the fact that it was also severely corroded. Since corrosion was not identified in the codes or comments, it was not found during the data mining process. This resulted in very few maintenance actions being found for the analysis. The second possibility stems from the fact that only three WUC's were studied, 11000, 22000, and 26000. This was due to time constraints on the study. While the three codes did reflect major systems on the aircraft, ideally, all WUC's should be included in the study.

This study involved condensing maintenance data for nine aircraft locations, resulting in an additional limitation. In general, when analyzing a sample statistically, a minimum of 30 data points is desired. The few data points used in this investigation resulted in plots that were very sporadic, making model creation difficult. Adding aircraft locations may result in a more accurate model, however, this is not guaranteed.

Statistics for each aircraft location were averaged. As a result, certain maintenance actions that took an excessive amount of time, or certain aircraft that had excessive problems may have influenced the data point for that location. This led to another limitation on the usefulness of the data for model creation.

The condition of each aircraft was not considered in the data analysis, leading to another limitation. Since each aircraft was overhauled as needed, the corrosive condition of the aircraft at the start of the six year analysis period could not be determined. This type of information is not included in the maintenance action database. Thus, aircraft that had not been overhauled in a long time might influence the data point for that location by representing the majority of repairs and labor hours.

Along with corrosive condition of the aircraft, the operational usage of the aircraft also could not be determined from the maintenance data. Aircraft may be flown over or near salt water, which is highly corrosive, although its home station may not have highly corrosive conditions. Thus, the aircraft operating in this condition would have more corrosion problems than an aircraft flown in a less corrosive atmosphere. Operational usage of an aircraft is yet another variable that should be accounted for when considering corrosion damage.

Results from the structural evaluation indicated that in depth data was needed in order to build an accurate understanding of the relationship between aircraft corrosion damage and atmospheric conditions. In this investigation, maintenance data alone was not enough to provide the level of accuracy needed to make a reliable prediction model. Observations made during the investigation were used to make recommendations for an improved study.

3.9 Recommendations

The system evaluation findings resulted in several recommendations for improved data mining from aircraft maintenance data. These recommendations were based on improvements that could be made to the maintenance database system, and implementing a corrosion monitoring system.

- Include all work unit codes.
- Include part numbers in maintenance records.
- Allow for the selection of multiple HM codes.
- Implement a corrosion monitoring system.
    - Use corrosion sensors to gather accurate corrosion rate data.
    - Continue data mining efforts and data comparison.

This investigation was performed using three work unit codes, however, there were many more that could reveal additional corrosion related maintenance actions. For example, fuselage components, landing gear, and rotor system work unit codes would also encompass components critical to flight. For this reason, it was recommended that all work unit codes be used in future investigations.

Due to the vague nature of maintenance action descriptions, it was difficult to determine the exact part that was repaired or replaced, as part numbers are not used. Descriptions provided a general idea on what assembly was damaged, however, if the part description was not exact, determining the specific component that was corroded became difficult. If maintenance actions included part numbers, a more in depth analysis could be performed, to calculate the exact amount of cost that would be saved by avoiding replacements.

As discussed previously, only one HM code is allowed for each entry into the maintenance database. If a component failed due to cracking, but was also damaged by corrosion, the HM code would only reflect the failure due to cracking. Due to the coupling nature of corrosion with fatigue cracking, the database should allow for multiple HM codes to be entered for each maintenance action. This would assist in future data mining efforts that study not only corrosion damage, but also combinations of conditions that combine to cause component failure.

Accurate data can be gathered through a corrosion monitoring system. As previously mentioned, the operational usage of the aircraft could not be determined in this investigation. It was assumed that the atmospheric conditions experienced by the base were representative of the conditions experienced by the aircraft. Employing sensors on the aircraft will assist in incorporating the operational use of the aircraft in the factors for corrosion damage. Sensors on aircraft that frequently fly over salt water will reflect this increase in corrosive atmospheric conditions. In addition to accounting for operations, the sensors will provide accurate corrosion rate data, that can be later studied along with damage data to investigate relationships and build better prediction models.

In addition to providing useful data, the corrosion monitoring system has the potential to reduce the occurrences of replacements, by providing an opportunity to treat the corrosion damage before a replacement is needed. This would significantly reduce maintenance costs, both in terms of the cost of the component and the cost of maintenance labor.

Once the corrosion monitoring system is in place, data mining efforts should continue. This would allow for side by side comparison of corrosion rates, atmospheric conditions, and maintenance actions. This would assist in calculating the cost of corrosion, and the cost savings of implementing the system.

3.10 Summary

Structural evaluation was accomplished through the analysis of aircraft maintenance data. The effort was divided into six steps. The first three steps involved analyzing maintenance information in order to identify problem areas and prepare the data for modeling. Location was converted to TOW and SO_2. Discrepancy information was converted to aircraft area and corrective action was converted into a binary number. Statistics such as average MTTR, repairs, replacements, and total LMH were summarized for each location. The result was nine data points, one per location, that contained the summary statistics.

By comparing maintenance actions and time for each aircraft area, the most problematic areas of the aircraft were found. The cabin & landing gear, engine, and tail boom were the three most problematic areas in terms of frequency. The center fuselage, engine, and tail boom were the most costly in terms of maintenance time. These areas were important considerations for sensor placement in the system design effort. Trends in corrective action were also observed. Twice as much time was being spent doing replacements as doing repairs. In addition, replacements were being done twice as often for repairs.

The second three steps consisted of building a prediction model and evaluating it for usability. Corrosion damage was examined for each climate area, in an effort to determine whether location had an influence on the observed damage. This involved developing an empirical model and evaluating the model for goodness of fit. Variables of influence were TOW and SO_2, while responses were MTTR, LMH, Repairs, and Replacements. A screening analysis was performed for the variables of influence, and it was found that three out of four responses had significant variables. These three responses were then modeled using the variables that passed the significance test. Once a prediction expression was obtained, it was evaluated for usability. It was found that none of the prediction models passed the evaluation, mainly due to high amounts of error and spread among the data.

The models created in this study did not accurately represent the maintenance data. This result suggests that maintenance data alone is not enough to provide the level of accuracy needed to make a reliable prediction model. Several recommendations were made to improve the quality of data found through aircraft maintenance data mining for future investigations. The most significant recommendation was to implement a corrosion monitoring system, to acquire the accurate atmospheric and corrosion rate data needed to develop significant prediction models.

Before a corrosion monitoring system can be implemented, it needs to be designed to fit the UH-1 aircraft. Careful consideration must be given to the user's needs, to ensure that the resulting system meets requirements and is effective. This is covered in the system design effort of this investigation.

CHAPTER 4: SYSTEM DESIGN

4.1 Overview

What corrosion monitoring system design would be most beneficial to the UH-1 aircraft? In order to answer this question, a methodology was needed to assist in developing a conceptual design and making a final decision on the configuration. One such methodology is the Integrated Product and Process Development (IPPD) methodology. The IPPD methodology is a generic top-down decision making processes. The IPPD methodology for systems engineering is a method designed to optimize product and processes in order to meet objectives in cost and performance [41]. It was mandated for Department of Defense use in 1995, and thus was an ideal choice for this investigation.

Figure 43 shows the generic IPPD methodology steps that were used in this investigation. There are six main steps of the method: establishing need, defining the problem, establishing value, generating feasible alternatives, evaluating alternatives, and making the final decision.

To establish need, it was important to recognize the deficit in current methods and the gap to be bridged by this effort. In defining the problem, the user and engineering requirements of the desired system were determined, ranked, and quantified. Requirements were used to set specific target values for system attributes. To establish value, results from the problem definition section were used to develop a metric to determine how well the designed system met the target objectives. Generating feasible alternatives was next, and involved compiling a list of possibilities that satisfy the user requirements into a morphological matrix. For every attribute, an alternative was selected to develop a conceptual design of the system. This alternative was evaluated against the target objectives. The final decision was then made based on the ability of the system to meet the objectives.

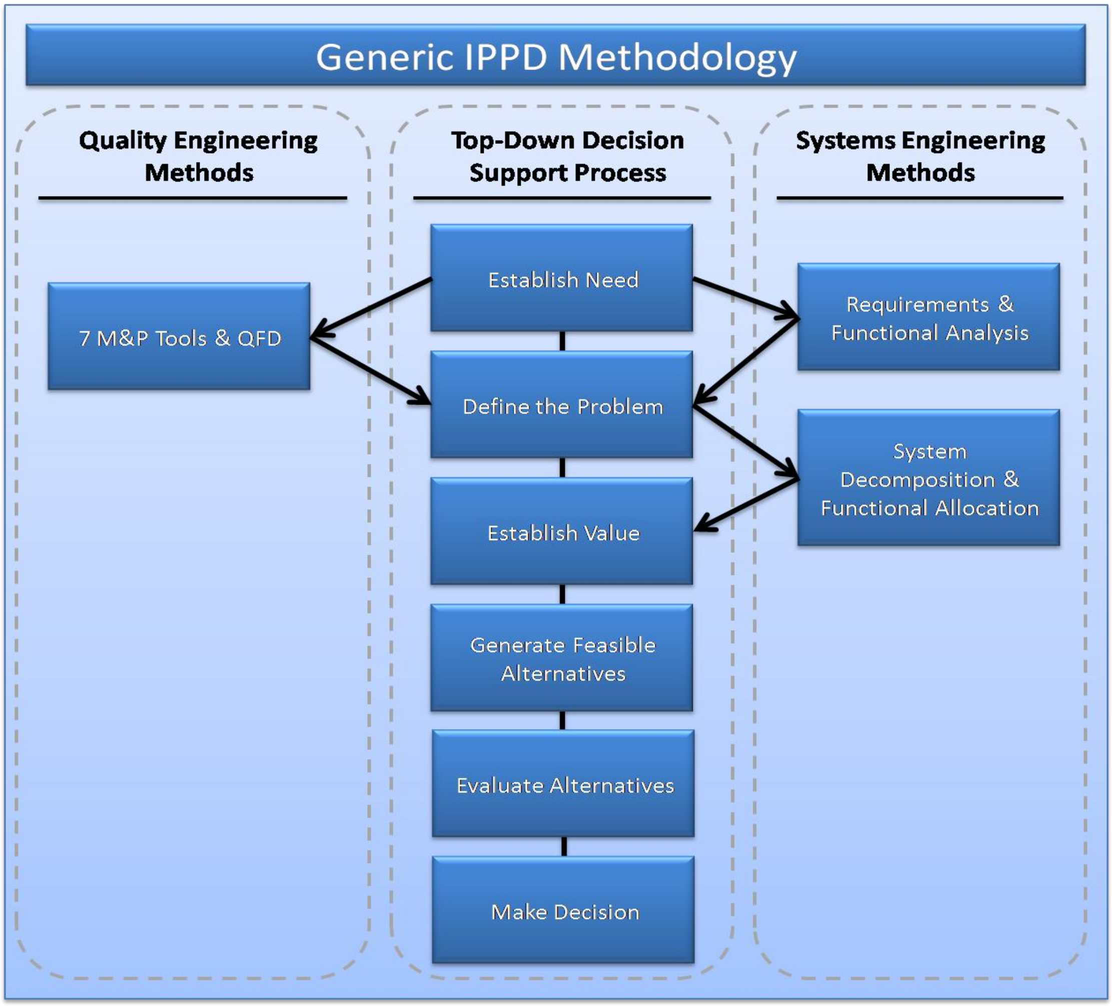


Figure 43: Generic IPPD Methodology

4.2 Establish Need

To establish need, it was important to recognize the deficit in current methods and the gap to be bridged by this effort. As mentioned previously, corrosion is recognized as a prominent structural issue. Corrosion damage raises sustainment effort and money needed to keep the aircraft safe for flight. Early detection has several benefits that can be realized through a corrosion monitoring system.

4.3 Define the Problem

In defining the problem, the desired traits of the system were determined and quantified. The seven management and planning tools were essential to this step of the IPPD methodology. The tools that were utilized in this investigation included the interrelationship diagraph, tree diagram, and prioritization matrices.

First, user and engineering requirements were defined. A functional analysis was performed to identify the operational, functional, and physical system functions and decomposition. The quality function deployment (QFD) was then used to analyze relationships between user requirements and engineering attributes.

4.3.1 System Requirements

In order to design a corrosion monitoring system (CMS), the system requirements must first be developed. What are the requirements for a corrosion monitoring system? Although varying requirements have been recommended by literature sources [10][11], some common threads exist and were combined together to create well-rounded requirements for the system.

Requirements were defined in two ways, for the user and for the engineer. The user requirements represented the top level requirements for the system as a whole. The engineering requirements were defined as specific system attributes that were investigated to ensure that the user requirements were fully met.

4.3.1.1 User Requirements

User Requirements were first created by listing general requirements for the system along with any related ideas, shown in the affinity diagram in Figure 44. Affinity diagrams are a result of initial brainstorming. It comprises a bottom-up approach that is useful for recognizing similarity among ideas for user requirements and grouping these ideas into appropriate categories. As shown in the image, requirements were broken down into three general categories: capability, dependability, and feasibility.

System capability refers to how well the system is able to perform its functions. It was important that the monitoring system provide data that is accurate, to depict the correct picture of the condition of the aircraft structure.

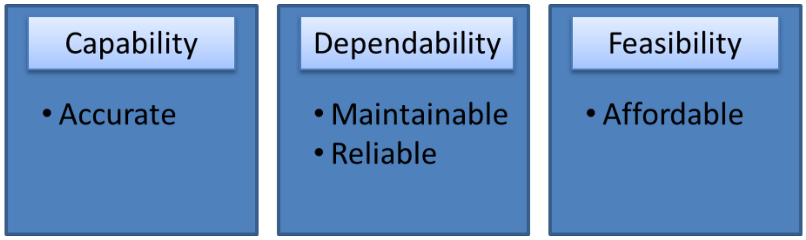


Figure 44: User Requirements Affinity Diagram

Dependability refers to how well the system performs its functions at any given time. This factor included both maintainability and reliability.

Maintainability describes the ability of the system to be restored to a specific condition by normal maintenance activities. Unfortunately, for many health monitoring systems, it is often the case that significant disassembly may be required in order to reach the system components. Ideally, minimum disassembly and effort should be required to maintain the corrosion monitoring system (CMS).

Reliability, another factor of dependability, is represented by the amount of time in which the system functions without failure. This feeds into dependability, as frequently repairing failed parts results in additional labor time and additional costs.

Feasibility, the last category of requirements, is a measure of how likely this system design will be achievable. This factor included affordability, as cost effectiveness plays a major role in deciding to implement a new system. The usefulness of the system should be comparable with the cost to acquire and maintain the system. Recall that the purpose of the CMS is to save valuable maintenance time and avoid potentially costly structural failures from corrosion damage. Therefore, time needed to maintain the system will be an important factor in evaluating the system effectiveness.

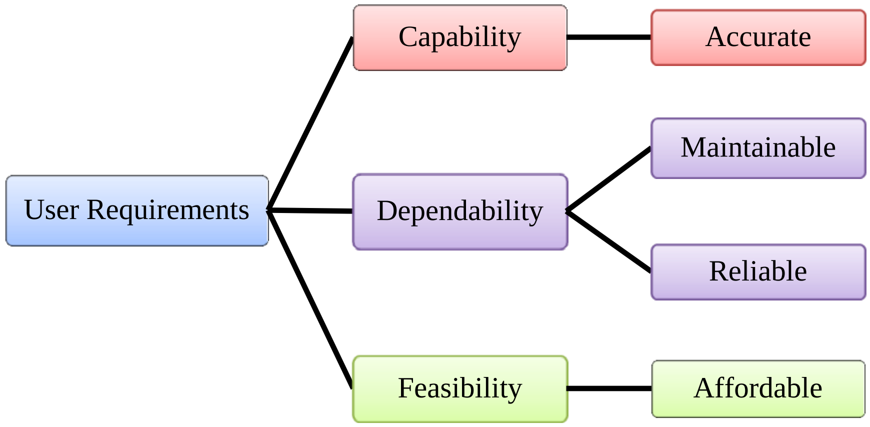


Figure 45: System Requirements

User requirements are shown in tree diagram form in Figure 45. The tree diagram takes information from the affinity diagram and organizes it into a top-down requirements decomposition. It increases in complexity as requirements are broken down into additional levels of detail.

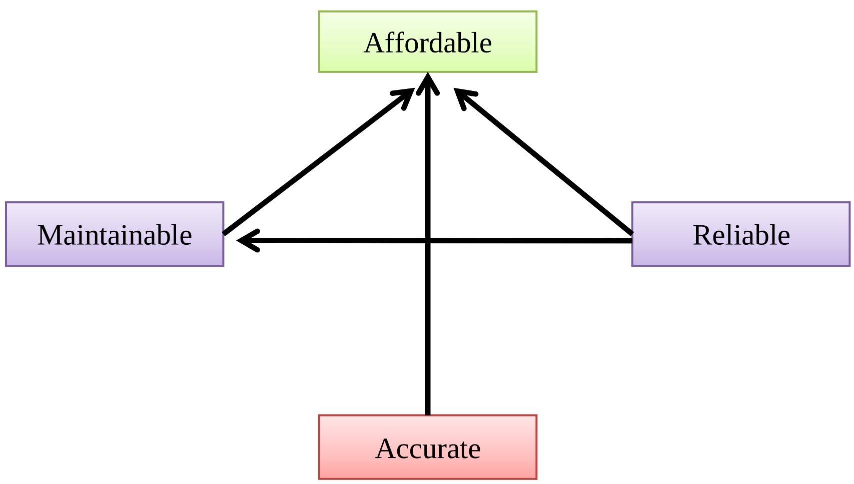


Figure 46: User Requirements Interrelationship Diagraph

An interrelationship diagraph was created for the user requirements and is shown in Figure 46. Interrelationship diagraphs are used to visualize cause and effect. Arrows are drawn to identify that the requirement has an influence on the requirement it points to. It is easy to see from the diagraph that the user requirements will be very influential on the affordability of the system. It would be a juggle between keeping the system accurate, reliable, and maintainable without compromising affordability. It is not obvious at this point how the requirements would influence each other, only that there was a cause and effect relationship among them.

Table 10: Prioritization Pattern

Value	Description
10	Much More Important
5	More Important
1	Same Importance
0.2	Less Important
0.1	Much Less Important

Once the system was broken down and the system attributes were determined for meeting user requirements, a prioritization matrix was developed. This matrix, another of the seven management and planning tools, gives a priority ranking of the customer requirements, by comparing the requirements against each other. The rankings input into the prioritization matrix followed the pattern in Table 10. A ranking of "10" indicates great importance, while a ranking of "0.1" indicates least importance.

		User Requirements				Ranking	
		Affordable	Reliable	Maintainable	Accurate	Requirement Weight	Requirement Importance (%)
User Requirements	Affordable		1	0.2	1	2.2	8.9
	Reliable	1		5	0.2	6.2	25.0
	Maintainable	5	0.2		0.2	5.4	21.8
	Accurate	1	5	5		11	44.4

Figure 47: Prioritization Matrix

A prioritization matrix for the CMS is shown in Figure 47. Every characteristic listed on the left was compared with every other characteristic listed on the top. The pattern described in Table 10 was used to determine which requirements had the most impact on the system design. Each row of values was totaled to obtain the weighted value, shown in the green highlighted column marked "Requirement Weight". The relative importance was then calculated by dividing each weighted value by the sum of all weights, and was included in the "Requirement Importance" column.

A Pareto Chart, shown in Figure 48, shows the ranking of the requirements from highest to lowest. Pareto Charts demonstrate the principle that the design for a system can be influenced by only a few requirements [58]. It was easy to see in this case that the first three requirements will drive the decision making for the entire system, as they represent 80% of the cumulative importance.

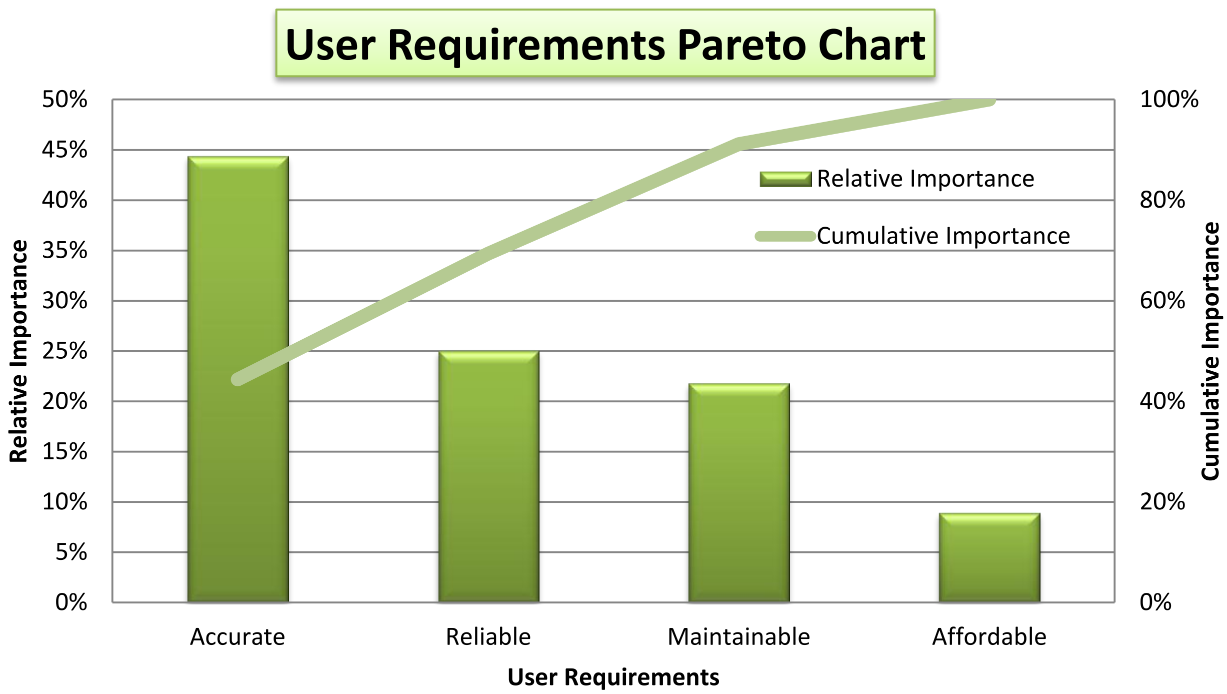


Figure 48: User Requirements Pareto Chart

Accuracy was the highest ranking requirement for the system. The main goal of the corrosion monitoring system is to provide an accurate picture of the condition of the structure. If the system is not accurate, then it will not provide a correct assessment, and will also not provide the information needed to develop predictive models. As expected, reliability and maintainability also ranked high. If the system requires too much time and effort to keep it maintained, then it is costing more than it is saving.

4.3.1.2 Engineering Requirements

Once user requirements were analyzed, engineering requirements were developed by defining system attributes that need to be considered in order for the system to meet the user requirements. An affinity diagram was developed, and is shown in Figure 49. The figure shows the same user requirements and adds another level of detail to account for specific system attributes. Attributes were identified and grouped according to the categories as shown in the figure.

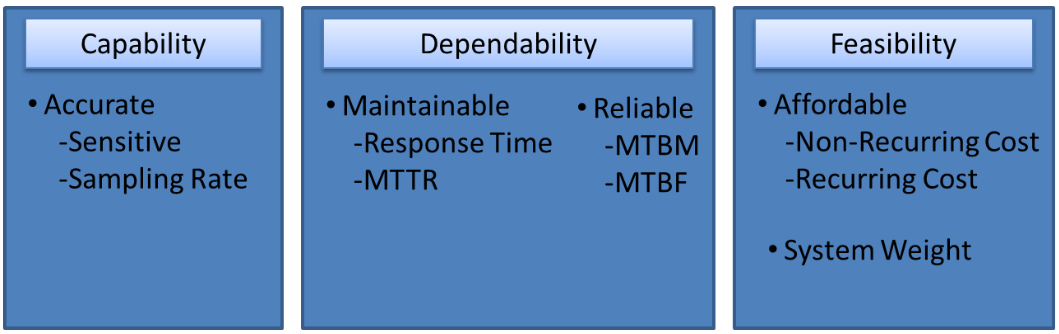


Figure 49: Engineering Requirements Affinity Diagram

A tree diagram for the engineering requirements is shown in Figure 50. It shows a top-down decomposition of the engineering requirements. As with the affinity diagram, there is an added level of detail that extends from the user requirements.

The user requirements state that the system must be accurate for it to be capable. Accuracy has been broken down into sensitivity and sampling rate. Sensitivity describes the smallest change in corrosion that can be detected in millimeters per year. Sampling rate refers to how often data is sent from corrosion sensors to the data logger, and is expressed in Hz, or samples per second.

Response time refers to the total amount of time it takes for data to go from the corrosion monitoring sensors to a wingman's desk, analyzed and ready for interpretation. It was important to minimize the response time of the system, and ultimately, total time required to maintain the CMS.

MTTR, or mean time to repair, refers to the average amount of time required to make repairs to the system. A minimized MTTR is ideal, so that the system can be repairable in a minimum amount of time.

The second factor of dependability is reliability. In a reliable system, repairs are infrequent and unexpected system failures are minimized. This translates to a high mean time between maintenance and mean time between failure. A high MTBM indicates a low frequency of maintenance actions needed to maintain the system. A high MTBF implies a system that has few unexpected component failures that cause additional unplanned maintenance labor and possible interference with aircraft operations.

Affordability includes both recurring and non-recurring system costs. Non-recurring cost includes the cost to develop and acquire the system. The cost to develop the system is captured in research, development, testing, and evaluation (RDT&E) cost. This cost can be eliminated, by using products that are currently available in the commercial market and adapting them for aircraft use. This is significant, as RDT&E costs are usually far greater than the system itself.

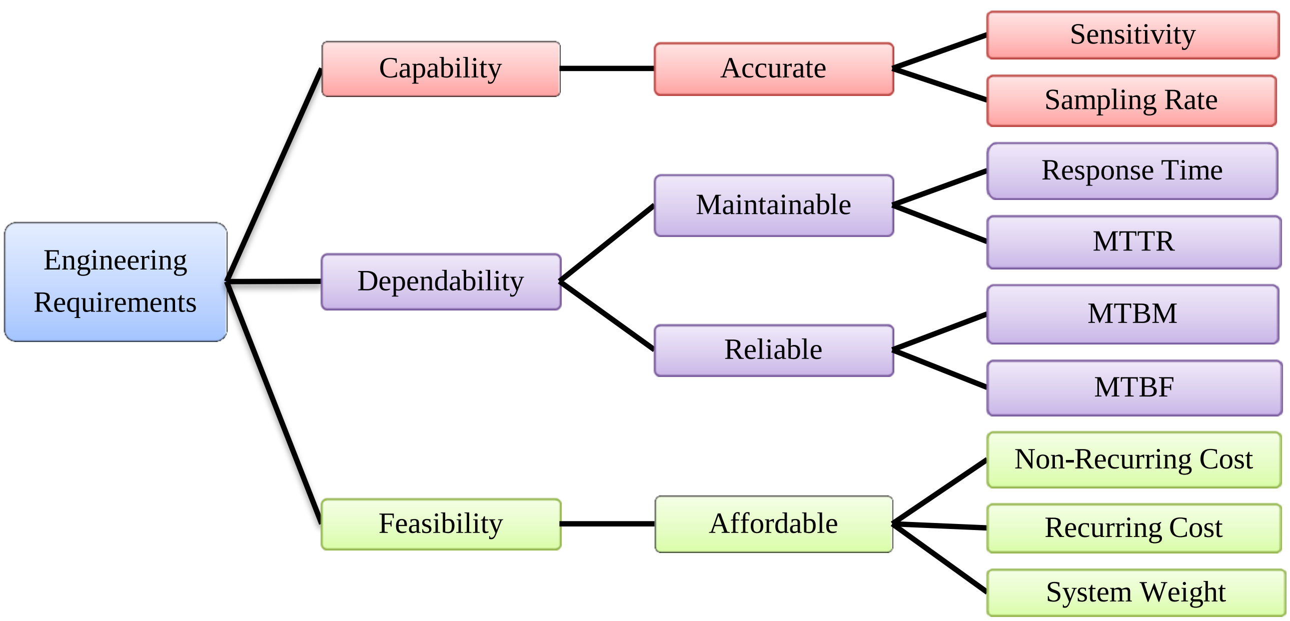


Figure 50: Engineering Requirements

Recurring costs include costs associated with maintaining the system, which include the labor required to maintain the system, as well as the cost of replacement parts. To reduce this cost, it was important to minimize the effort needed to maintain the CMS.

As with all aircraft, system weight was very important. Adding systems adds weight to the aircraft, reducing its payload and range capability. To minimize impact on aircraft capability, the system was required to be very light. There should be sufficient data capture, without excessive weight.

An Interrelationship diagraph was created for the engineering requirements and is shown in Figure 51. The majority of system attributes affected the recurring and non-recurring costs of the system. This was typical, as operating and maintaining the system require maintenance effort, which contribute to the recurring cost. The performance of the system, captured by the sensitivity, sampling rate, and failure rates, had a large effect on the acquisition cost, which was included in the non-recurring cost of the system. Note that this was reflected in the interrelationship diagraph for the user requirements, in which most of the requirements were pointing to affordability.

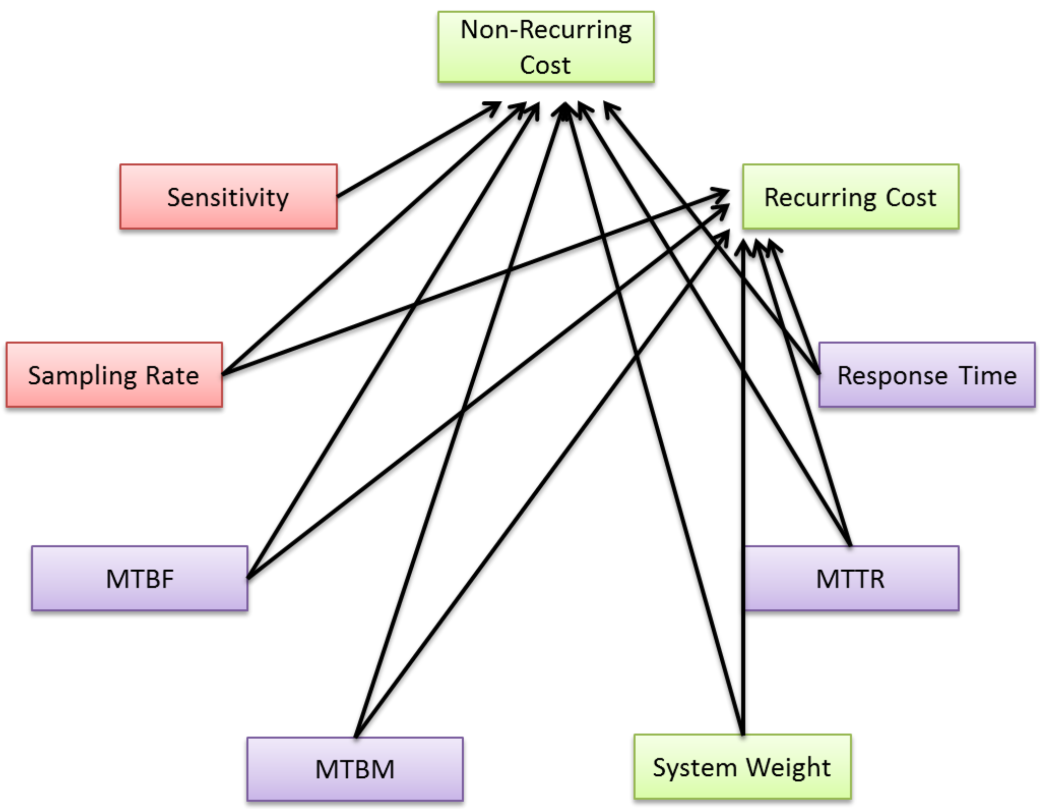


Figure 51: Engineering Requirements Interrelationship Diagraph

Engineering requirements were placed in a prioritization matrix and ranked, as shown in Figure 52. The prioritization ranking pattern is shown in Table 10. Sensitivity and sampling rate ranked the highest of all the requirements. This matches the user requirement rank list, in which capability was shown as most important. The next group of requirements ranked nearly the same. MTBF, MTBM, and MTTR ranked at about 15% relative importance. This was expected, as the CMS should cost little time and effort to maintain. The least important requirements were response time, weight, and cost. These parameters may have ranked low in the prioritization matrix, but they are also important for consideration. A system that costs or weighs too much would not be beneficial.

		Feasibility			**Dependability**				**Capability**		**Ranking**	
		System Weight	Recurring Cost	Non-Recurring Cost	Response Time	MTTR	MTBM	MTBF	Sensitivity	Sampling Rate	Requirement Weight	Requirement Importance (%)
Feasibility	System Weight		5	5	0.2	0.1	0.1	0.1	0.2	0.2	10.9	5.0
	Recurring Cost	0.2		10	0.2	1	0.2	0.2	0.1	0.2	12.1	5.6
	Non-Recurring Cost	0.2	0.1		0.2	0.2	0.2	0.2	0.1	0.1	1.3	0.6
Dependability	Response Time	5	5	5		1	0.2	0.2	0.1	0.1	16.6	7.6
	MTTR	10	1	5	1		0.2	0.2	1	10	28.4	13.1
	MTBM	10	5	5	5	5		0.2	1	0.2	31.4	14.5
	MTBF	10	5	5	5	5	5		1	0.2	36.2	16.7
Capability	Sensitivity	5	10	10	10	1	1	1		1	39	18.0
	Sampling Rate	5	5	10	10	0.1	5	5	1		41.1	18.9

Figure 52: Engineering Requirements Prioritization Matrix

A Pareto Chart for the engineering attributes is shown in Figure 53. The first five requirements represented 80% cumulative importance. This is indicative of the fact that processes tend to be dominated by only a few requirements.

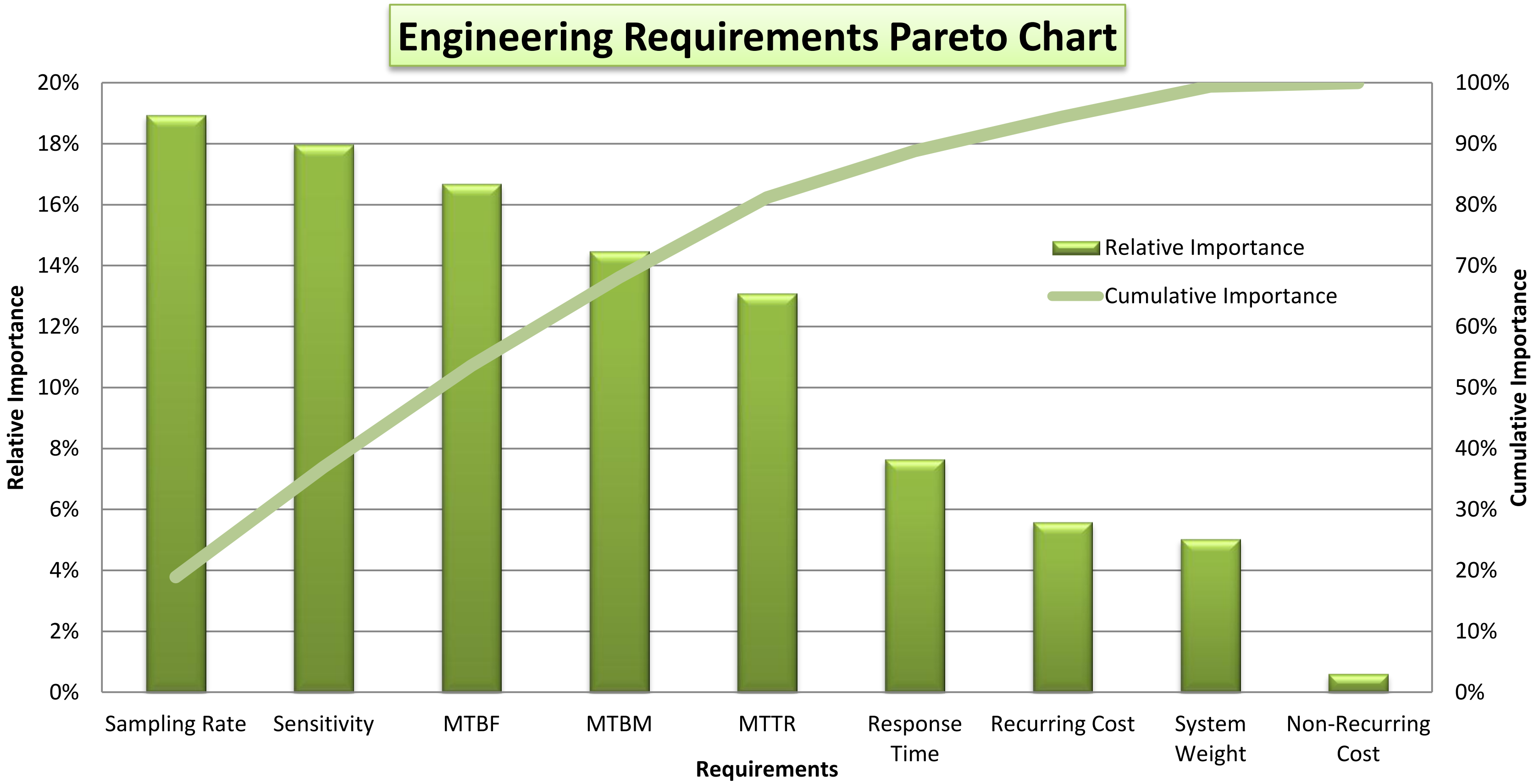


Figure 53: Engineering Requirements Pareto Chart

4.3.2 Functional Analysis

A functional analysis focused on three views, the operational, functional, and physical architectures of the corrosion monitoring system. These three views were critical in ensuring that all user requirements were understood. The system serving its purpose was represented by the operational architecture. The functional architecture focused on what the system does in order to perform the mission. Lastly, the physical architecture described the components that comprise the system. [23]

4.3.2.1 Operational Architecture

The operational architecture, shown in Figure 54, gives a bottom-up overview of how information gained by the CMS can be used for fleet management. Information starts out at a local level, with each equipped aircraft monitored for corrosion damage. Data downloaded from each aircraft can be grouped for each location, and corrosion damage can be assessed at a group level. Finally, the data from each group of aircraft can be combined for an assessment of the overall UH-1 fleet. At the fleet level, decisions can be made on implementing different corrosion management strategies for all aircraft within the fleet.

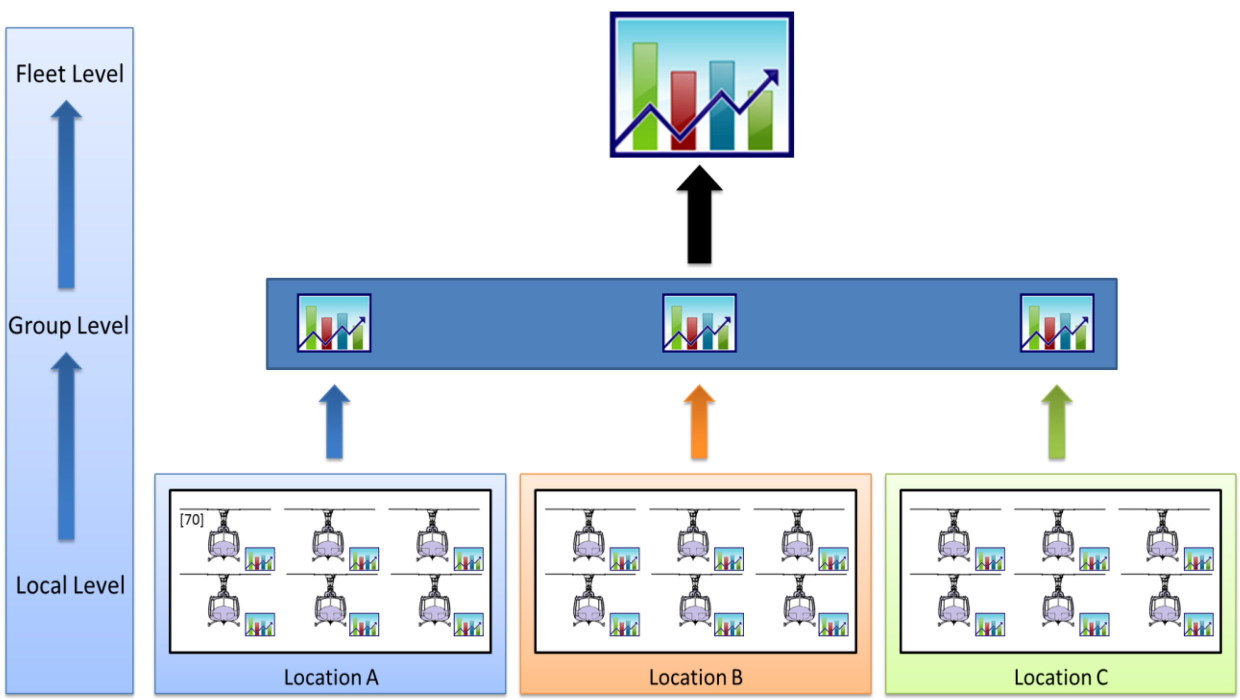


Figure 54: Operational Architecture

4.3.2.2 Functional Architecture

The functional architecture, shown in Figure 55, described what the system does to perform its mission. In this case, the system mission was to monitor corrosive activity of aircraft structure. The monitoring system works by continuously capturing data on the atmosphere and condition of the aircraft structure. The captured data is stored into a storage device, where it stays until it is downloaded by aircraft crews. The data is then processed and visualized by software installed in local computers. The process of downloading and processing data is continuously repeated while the monitoring system is in place.

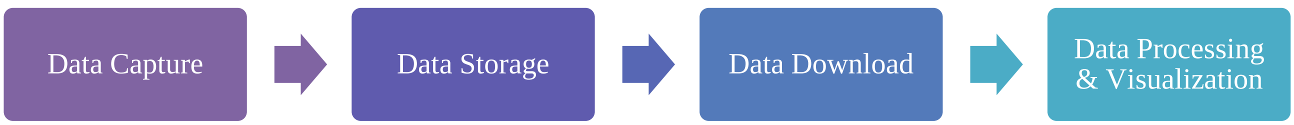


Figure 55: Functional Architecture

4.3.2.3 Physical Architecture

The CMS physical decomposition is shown in Figure 56. Components were divided between two main categories, on-board and on-ground. The on-board components included equipment that would be kept aboard the aircraft: power supply, sensors, data acquisition unit (DAQ), and all of the electrical wiring and other electrical components that make up the system. The on-ground component consists of the software that will analyze the data after it is downloaded from the aircraft data acquisition unit.

Sensors were divided into two types, corrosion and environmental. The corrosion sensors monitor damage to the structural components while the environmental sensors monitor the corrosivity of the atmosphere. Monitoring both areas assists in developing relationships between atmospheric conditions and corrosion damage experienced by the aircraft structure.

The on-ground components represented the parts of the CMS that remain on the ground at the aircraft's base of assignment. For a CMS, this would primarily include the software that is needed to analyze the data stored on the on-board DAQ. The software should be compatible with current operating systems so that it can be installed on computers already utilized by maintenance personnel.

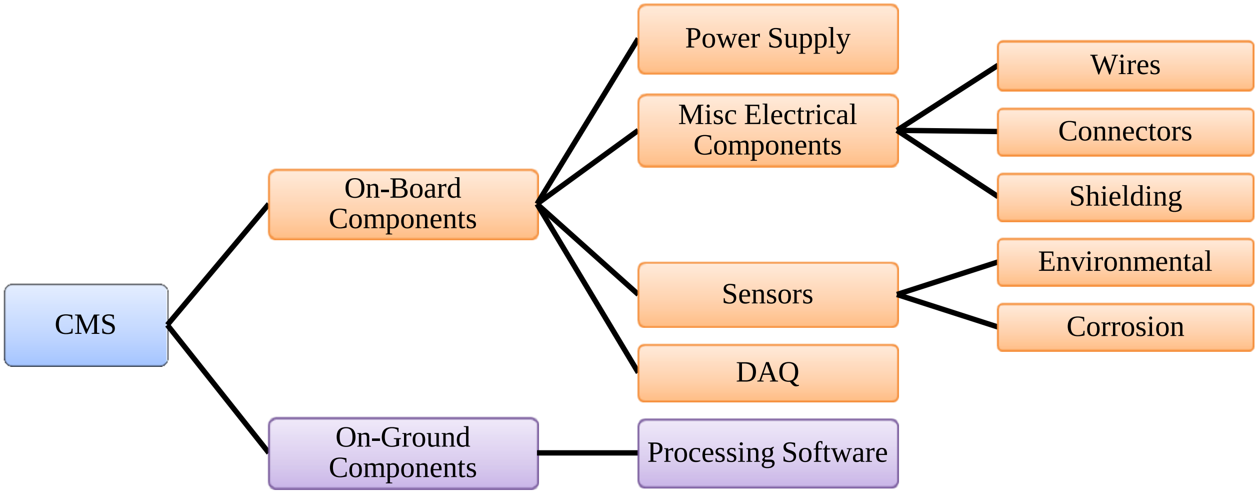


Figure 56: Physical Decomposition

4.3.3 Quality Function Deployment

The quality function deployment, or QFD, was used to express the customer requirements in terms of the system attributes necessary to meet those requirements. Target values were established for each system attribute, and the attributes were assigned a relative importance. This relative importance was based on the prioritization of the customer requirements as well as the relationship between the requirements and the attributes. Once a difficulty was assigned to the task of attaining each target value, a relative risk was assigned to the attributes. [6]

Figure 57 shows a diagram of the QFD configuration, also known as the House of Quality. The diagram was created using QFD Designer from Qualisoft [77]. The management and planning tools fed into the quality function deployment process. The tree diagrams helped develop the "How" and "What" rooms. The interrelationship matrix came into view in the roof of the QFD, where trade-offs were investigated, and the prioritization matrix established the importance of each requirement. [58]

Figure 58 shows the symbols that are used to identify relationships in the QFD. Symbols were used to identify strong and weak relationships among requirements, as well as identify target value direction. Target value direction was identified as nominal best, larger the better, and smaller the better.

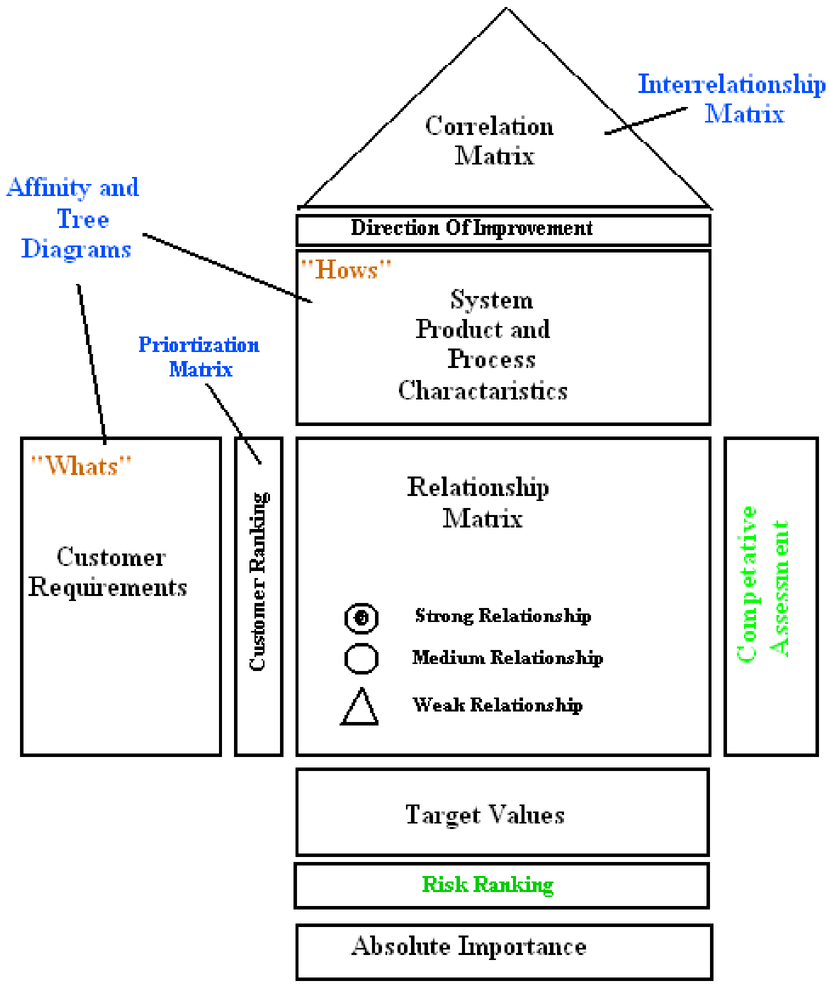


Figure 57: Quality Function Deployment [58]

Figure 59 shows the QFD for the CMS. The system attributes were divided into the same three categories as the system requirements, capability, dependability, and feasibility. Each of the attributes had a corresponding target value, difficulty level, importance, and risk. Target values were performance thresholds that the system is required to achieve. The difficulty level was represented by a non-linear scale of 1, 3, or 10, with 1 being the easiest, and 10 posing great difficulty. The greater the difficulty and the importance, the greater the risk associated with achieving that particular target value. Risk represented the probability that the target value will not be achieved, and was based on the difficulty rating.

Capability included sensitivity and sampling rate. The target value for sensitivity was 0.01mm/year. This was the minimum observed corrosion rate from samples taken at various locations [72]. The target value for sampling rate was 0.00028 Hz, or one sample per hour. The benefit of having a low sampling rate is that less power is consumed, and the batteries used to power the system will last significantly longer. For this investigation, the sampling rate of 0.00028 Hz, or on sample per hour, was chosen due to the fact that corrosion grows at a very slow rate. In addition, the atmosphere also changes slowly, which would be adequately captured in one sample per hour.

Figure 58: Symbol Nomenclature

Dependability included response time, MTTR, MTBM, and MTBF. The desired value for response time was 3 LMH. MTTR was chosen to be 2 LMH. The target value for MTBM and MTBF was 300 flight hours (FH). The system should require a minimal of maintenance time to operate and maintain. The 300 FH failure rate guarantees that system components will not fail for a minimum of one year.

Non-recurring cost, recurring cost, and system weight were included in feasibility. The non-recurring, or acquisition, cost of the system was set at a maximum of $100,000. Recurring cost was set to a maximum of $10/FH. System weight should be under 10lbs.

The difficulty expected in achieving the target values was displayed in the "Organizational Difficulty" row of the QFD. The most difficulty was projected to be in achieving a low MTTR, a high MTBM, a high MTBF, and a low system weight. This was expected, as MTTR, MTBM, and MTBF were the primary drivers in the amount of time, and thus cost, it will take to maintain the system. If the system design does not meet these objectives, there is little incentive to acquire the system. Also of high interest are the non-recurring and recurring cost. The non-recurring cost was driven by the cost to acquire the system, while the recurring cost was mainly driven by the MTTR, MTBM, MTBF, and weight parameters.

Possible conflicting requirements are shown in the side roof and top roof of the QFD. The side roof shows the relationship among the user requirements. Both positive and negative relationships were identified, with most requirements posing an influence to affordability. This correlated with the interrelationship diagraph shown in Figure 46. The top roof shows relationships among the system attributes. Positive and negative relationships were be identified in the figure, especially among MTTR, MTBM, MTBF, and system costs. Figure 51 shows a similar relationship among the system attributes.

A benchmark comparison was included in the QFD, showing how current corrosion inspection techniques compare with the proposed corrosion monitoring system concept. Visual and non-destructive inspection (NDI) methods are currently used to evaluate corrosion damage. Visual inspections involve visually assessing the damage. NDI involves specialized equipment as well as specially trained personnel.

A scale is used for comparison, and includes values from 0 to 5. Zero identifies items that are not applicable to the inspection technique. Values from 1 to 5 are used to rank the technique from poor (1) to best (5). The Customer Assessment shown on the right of the QFD chart identifies how the inspection techniques compare with user requirements. The Technical Assessment shows how the inspection techniques rank according to the system attributes.

In general, the corrosion monitoring concept can compete with the other inspection techniques due to the accuracy and early warning capability that it provides. Visual inspection is the cheapest, however, it is also the most unreliable method. NDI is disadvantageous due to the time consuming nature of using the equipment to evaluate surface damage of a structural component. In addition, NDI inspection requires specially trained personnel. For these reasons, NDI is usually an expensive endeavor. Corrosion monitoring has the potential to save maintenance effort, although as with adding any system to an aircraft, there will be associated maintenance and recurring costs.

It is easy to see the interconnection among different parameters and requirements in the QFD diagram.

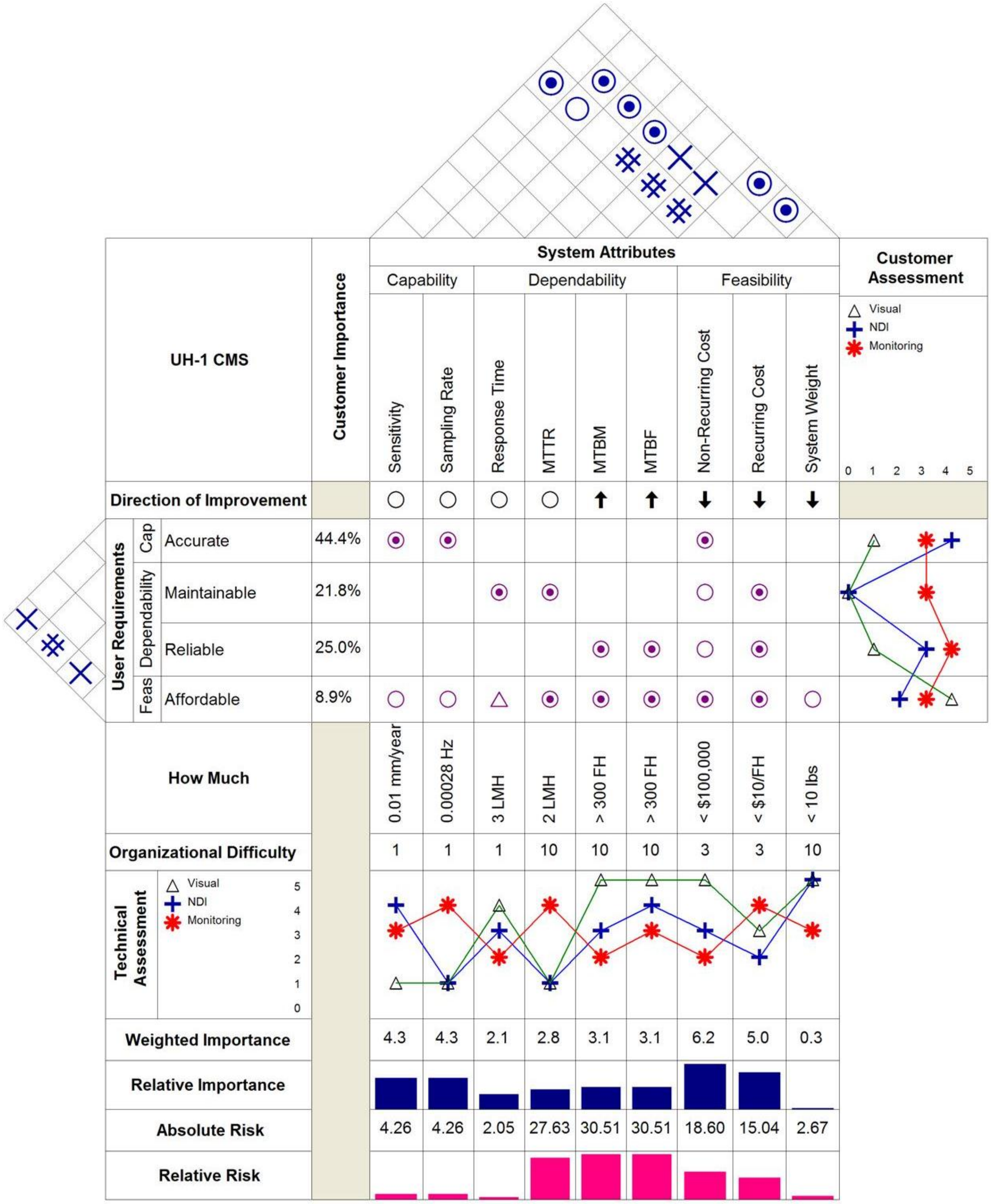


Figure 59: CMS Quality Function Deployment

4.4 Establish Value

Establishing value involves creating metrics that are used to evaluate the selected system design against the original requirements. The criteria consist of the engineering requirements, listed in Table 11, that were established earlier in this chapter. The goal for each requirement is also listed, identifying whether it is best to minimize or maximize the design value.

Table 11: Design Target Values

Requirement	Target Value	Goal
Sensitivity (mm/year)	0.01	Minimize
Sampling Rate (Hz)	0.00028	Minimize
Response Time (LMH)	3	Minimize
MTTR (LMH)	2	Minimize
MTBM (FH)	300	Maximize
MTBF (FH)	300	Maximize
Non-Recurring Cost ($)	100,000	Minimize
Recurring Cost ($/FH)	10	Minimize
Weight (lbs)	10	Minimize

For each requirement, an nondimensionalized index was created, such as the one for sensitivity shown in Equation 1. The equation shows the target value for the requirement in the numerator, and the actual value achieved by the system design in the denominator. The equation was arranged in this fashion due to the fact that it is ideal to have a smaller sensitivity. If the design includes a sensitivity that is less than 0.01 mm/year, then the resulting index will be greater than 1. Thus, the design would be considered acceptable for this criterion.

$$Sensitivity\ Index = \frac{0.01\ (\frac{mm}{year})}{Sensitivity\ (\frac{mm}{year})} \qquad \textbf{Equation 1}$$

The equation for the MTBF Index is shown in Equation 2. In this case, it is best to maximize MTBF, so the actual design value will appear in the numerator. If the design MTBF is greater than the 300 Flight

Hour (FH) requirement, then the index will be greater than 1. The design goal is to achieve an index that is greater than or equal to 1 for each of the requirements.

$$MTBF\ Index = \frac{MTBF\ (FH)}{300\ FH} \qquad \textbf{Equation 2}$$

The remaining equations for each requirement index are shown in Equation 3 through Equation 9.

$$Sampling\ Rate\ Index = \frac{0.00028\ Hz}{Sampling\ Rate\ (Hz)} \qquad \textbf{Equation 3}$$

$$Response\ Time\ Index = \frac{3\ LMH}{Response\ Time\ (LMH)} \qquad \textbf{Equation 4}$$

$$MTTR\ Index = \frac{2\ LMH}{MTTR\ (LMH)} \qquad \textbf{Equation 5}$$

$$MTBM\ Index = \frac{MTBM\ (FH)}{300\ FH} \qquad \textbf{Equation 6}$$

$$Non - Recurring\ Cost\ Index = \frac{\$100{,}000}{Non - Recurring\ Cost\ (\$)} \qquad \textbf{Equation 7}$$

$$Recurring\ Cost\ Index = \frac{10\ \$/FH}{Recurring\ Cost\ (\frac{\$}{FH})} \qquad \textbf{Equation 8}$$

$$Weight\ Index = \frac{10\ lbs}{Weight\ (lbs)} \qquad \textbf{Equation 9}$$

The final value for each index will be calculated once the conceptual design is determined.

4.5 Generate Feasible Alternatives

This step in the IPPD methodology involved compiling a list of possibilities that satisfy the user requirements into a morphological matrix. The morphological matrix, or matrix of alternatives, is a method of visualizing alternatives that meet the system requirements. This matrix is a tool that can be used to identify unconventional solutions that may not otherwise be evaluated. The matrix answers the question: what technology is available for use?

The matrix of alternatives for the CMS is shown in Table 12. System functions that were defined in the functional architecture were listed in the first column. Then, attributes of the system that accomplish the functions were listed in the second column. The remaining columns include the feasible options, or alternatives, of each attribute.

Table 12: Matrix of Alternatives

Function	Attribute	Alternatives			
Data Capture	Corrosion Sensor Type	Coupon	Electrical Resistance	Galvanic	Linear Polarization Resistance
	Power Source	Battery	Line	Solar	
	Technique	Intrusive	Non-intrusive		
	Environment Sensor Type	Temperature	Humidity	Pressure	Time of Wetness
	Installation	Carry-on	Permanent		
	Application	Metal Surface	Coating		
Data Storage	Data Storage Device	Data Logger			
Data Retrieval	Data Download	Wireless	Wired	Flash	
	Data Retrieval	Real-Time	Off-line		

The first and most essential function of the system is to capture corrosion data. Several different types of sensors can be used to monitor corrosion, including coupons, electrical resistance, galvanic, and linear polarization resistance (LPR). Coupons are small blocks of the material of interest that are inserted into the corrosive environment. Later, the coupon is removed and the corrosion products that have covered the surface are cleaned and the coupon is weighed. The difference in the initial and final weight provides an average corrosion rate in material loss per unit time. Electrical resistance sensors measure the electrical resistance of a small exposed element. When the element experiences weight loss due to corrosion, its electrical resistance also changes, providing an indirect method for calculating corrosion rate. Galvanic sensors use the principal of dissimilar metals. When two dissimilar metals touch in an electrolyte solution, current is produced due to the potential difference between the two metals. This current is measured and related to corrosion rate. LPR sensors work by placing a metallic element in an electrolyte solution. A specific voltage is maintained artificially, and the current needed to maintain that voltage is measured.

This current can be directly related to corrosion rate. LPR sensors are the only type of sensor that can provide real-time corrosion rates. [1]

With the exception of coupons, all of the mentioned sensors involve a power source for taking measurements. There are several different power options, including battery, aircraft (line), and solar. Batteries need to be periodically replaced, although not having to connect to aircraft power would reduce the amount of wiring required for the system. Using aircraft power would require tying the CMS directly to the aircraft power system. The third option, solar power, requires the placement of a solar panel somewhere on the aircraft.

Techniques for taking corrosion measurements vary depending on whether intrusive or non-intrusive methods are used. Intrusive measurements involve placing sensors inside the material that is to be monitored. Using intrusive sensors would mean permanently scarring the structure that is being monitored. Non-intrusive techniques involve placing the sensors on the outside of the material. This is a no-scars method of installation, and is often the more preferred method.

Along with monitoring the structure itself, it is also useful to monitor the environment. This data can later be used to develop prognostic tools that relate environment to corrosion of the aircraft structure. The environment can be monitored several ways, including temperature, humidity, pressure, and time of wetness.

There are two main options for installation, carry-on and permanent. A carry-on system is designed to be carried on to the aircraft for a short period of time, and subsequently removed. The system would ideally be installed with minimum damage to the aircraft. A permanent system would stay with the aircraft for life, and could be installed in a more permanent fashion.

Monitoring systems can be used to monitor the integrity of the metal surface or the condition of coatings. Since coatings exist mainly to prevent corrosion damage, monitoring the coating integrity may also be beneficial.

Data storage is accomplished with a data logger device that is part of the system installed on the aircraft. The data logger is capable of storing a large number of samples, until the information is downloaded onto a local computer.

At some point the data needs to be downloaded from the data logger. This can be accomplished either with wires connecting to a local computer, wirelessly, or via flash memory. The frequency in which data is downloaded would depend on the aircraft maintenance schedule. For this study, a download frequency of once per month was assumed.

Data retrieval can be accomplished either in real-time or off-line while the aircraft is down for maintenance.

The complete matrix of alternatives reveals 2304 possible combinations of components to create the corrosion monitoring system. Each alternative must be evaluated, so that the chosen system represents the best possible choice. Then, the system in its entirety is evaluated against the engineering requirements.

4.6 Evaluate Alternatives

For every attribute, an alternative was selected to develop a conceptual design of the system. Decisions were based on anticipated preferences for the users, and were explained in depth for each system attribute. The highlighted items in Table 13 show which alternatives were ultimately selected. The conceptual configuration was then matched with a commercial-off-the-shelf system currently available.

4.6.1 Select Conceptual Design

For the first attribute, corrosion sensor type, linear polarization resistance was chosen due to its applicability for aircraft structure, simplicity in use, and availability in the commercial market. LPR sensors provide highly accurate corrosion rate data, which can be easily collected using a data logger. Coupons, although a cheap solution, must be monitored by hand. This includes removing the coupon from the aircraft, cleaning it, and carefully measuring its weight. This is undesirable, as it only provides an average corrosion rate over a long period of time. It would also require significant maintenance time and effort to clean and reweigh each coupon on the aircraft. If there were a large number of coupons on each aircraft, the time required would add up quickly. In addition, using a coupon means logging and analyzing data by hand, another time consuming task. The LPR sensor was chosen over electrical resistance and galvanic sensors due to the fact that the LPR sensor is the only sensor that provides direct readings on corrosion rate.

Three power source alternatives were identified, battery, line, and solar. Solar power is not practical on an aircraft, since it would involve installing a solar panel on the outside of the aircraft. In addition, solar power can be inconsistent, as weather is a heavy influence on the amount of energy that can be collected. Both battery and line power can be solutions that work well for military aircraft. With battery power, there is no need to modify the aircraft power system, which reduces the impact that the installation has on the aircraft. Less modification equates to less impact on the aircraft, less cost for installation, and faster implementation. In addition, aircraft power would be left to more immediate mission needs. The disadvantage is that the batteries need to be periodically replaced. Replacement rate would be highly dependent on the sampling rate. With a low sampling rate, the batteries can last for up to 10 years. With line power, there is no need to change batteries, but as mentioned earlier it would require significant modification to the aircraft to enable an electrical connection. For this investigation, batteries were chosen as the desired power source, as they have a long life, due to the low power requirements of the sensors.

The sensors can be mounted on the structure in an intrusive or non-intrusive way. In this application, both methods provide the same type and quality of information. Since non-intrusive sensors would not require damaging the structure for installation, this method would be preferable over intrusive sensors.

Monitoring the environment around the structure may provide beneficial information when compared with corrosion rate measurements taken by the LPR sensors. There are many choices for monitoring the environment, however, there are a limited number of sensors on the aircraft. The few sensors that can be spared for environmental monitoring should be used wisely. For this investigation, time of wetness sensors may be the most beneficial, as they capture both temperature and humidity in the measurements.

The installation can be carry-on or permanent. Having a corrosion monitoring system aboard the aircraft long-term is beneficial. Each aircraft would have its own designated monitoring system. This would allow for accurate corrosion rate tracking on an individual aircraft basis. In addition, it would allow for a steady-stream of information, which is beneficial for identifying trends. If the carry-on approach is used, fewer systems would need to be purchased, as the systems could be temporarily used on one aircraft and then switched to another. Unfortunately, this would provide disjointed information for each aircraft. For this reason, permanent was chosen as the preferred installation method.

For this study, monitoring the structure was chosen over monitoring coating integrity. While monitoring coatings is also beneficial, focus will be placed on monitoring the structure directly.

A data logger was selected as the data storage device. The data logger may be a stand-alone unit, or an existing data acquisition unit that is already on the aircraft. While tying into an existing data acquisition unit would reduce the cost of the monitoring system, it may be beneficial to purchase a separate data logger due to the sensitivity of the measurements being made.

Data can be downloaded either wirelessly, with a wired connection to the data logger, or via flash memory. Downloading wirelessly is convenient, although it is more expensive than the other options. The data logger needs to be close to the sensors it is receiving data from. This means that the data logger may be buried in the aircraft, requiring hours of painstaking disassembly to reach. Having wireless download capability will eliminate the need to access the data logger, eliminating hours of maintenance work. For this reason, wireless was chosen as the preferred download method.

Data download can occur in real-time or off-line. For a military aircraft, off-line data retrieval is preferable, since it can be done at a convenient time when the aircraft is down for other maintenance.

Table 13: Conceptual Design

Function	Attribute	Alternatives			
Data Capture	Corrosion Sensor Type	Coupon	Electrical Resistance	Galvanic	Linear Polarization Resistance
	Power Source	Battery	Line	Solar	
	Technique	Intrusive	Non-intrusive		
	Environment Sensor Type	Temperature	Humidity	Pressure	Time of Wetness
	Installation	Carry-on	Permanent		
	Application	Metal Surface	Coating		
Data Storage	Data Storage Device	Data Logger			
Data Retrieval	Data Download	Wireless	Wired	Flash	
	Data Retrieval	Real-Time	Off-line		

4.6.2 The Analatom AN101W Corrosion Monitoring System

A commercial off-the-shelf system that includes the selected configuration from the matrix of alternatives was found from Analatom Inc. The Analatom system that fits the configuration shown in Table 13 is known as the AN101W system. The system included a data logger, eight sensors, and wireless capability. Figure 60 shows an LPR sensor without wiring (left) and one installed under a paint coating (right). The sensor is constructed from the same material that is being monitored, allowing it to corrode at the same rate as the structure. The sensor is mounted to the structure using epoxy, and is painted over and coated in the same manner as the structure. The sensor can be easily removed, should the structure need to be removed. In addition to detecting general corrosion, the LPR sensor is also capable of sensing ever elusive pitting corrosion. [73]

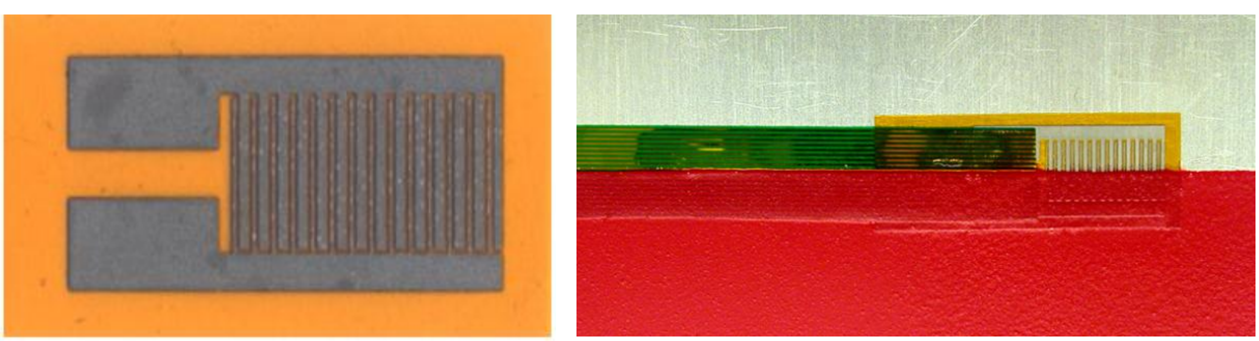


Figure 60: LPR Sensor [76]

An example installation of the data logger is shown in Figure 61. Each data logger can hold up to eight sensors. For the configuration in this study, two data loggers were needed, for a total of 16 sensors. Most of the sensors will be for corrosion, and the remaining will be used to monitor the atmosphere. By examining data from the corrosion and atmospheric sensors, potential relationships between the two can be identified. The data logger will be powered by batteries, and data will be downloaded wirelessly.

Figure 61: Data Logger Installation [74]

4.6.3 System Evaluation

Once the commercial system was chosen, it was evaluated against the user and engineering requirements developed in section 4.3. Table 14 shows how the system compares with the target values established for each criteria.

The first category, capability, includes sensitivity and sampling rate. Recall that sensitivity is the amount of thickness loss that can be detected by the sensor in units of mm/year. Sampling rate, displayed in Hz, is the number of samples taken per second. The target value for sensitivity was 0.01 mm/year. The achieved value for the system was 0.001mm/year, which is 10 times more sensitive than the target criteria [73]. The target value for sampling rate was 0.00028 Hz, which is one sample per hour. The target value was achieved, due to the fact that the data logger can be programmed to capture data at any desired sampling rate [73].

System dependability includes response time, MTTR, MTBM, and MTBF. The response time of the system includes downloading the data from the CMS, uploading it to a computer, and running the analysis software. Since the CMS has wireless download capability, the data logger does not need to be accessed directly. Maintenance personnel can stand well outside the aircraft and download all data within one minute, via a hand-held device [73]. Information can be downloaded quickly and easily uploaded to a nearby computer. The target value was 3 LMH, however the actual response time needed for the CMS was about 1 hour. This includes downloading the data from the aircraft, uploading the data to a nearby computer, and running the software.

The target value for MTTR was 2 LMH. Repairing the CMS would involve changing batteries in the data logger, and changing sensors that have met their service life. For the CMS, this action is very simple, however, a conservative estimate of 2 hours was assumed, in the case that multiple sensors need replacement at one time.

It was desired that the MTBM be greater than 300 flight hours, or about 1 year. The calendar assumption is based on the aircraft flying an average of 300 flight hours (FH) per year. Since maintenance is only needed when the battery dies, or when the corrosion damage to the sensor has exceeded its thickness, this target value is within reach. The LPR sensors have a thickness of 100µm [73]. Assuming a very high corrosion rate of 2mm/year, the sensor would have a service lift of 5 years, or every 1500FH. If a low corrosion rate is experienced, then the sensor would last far longer.

MTBF is also an important consideration for the system. The target value for this criteria was also 300 FH. The actual MTBF for the system is not known at this time [75]. There was one reported failure, which occurred in the laboratory, and not on an installed system. Battery life is expected to outlast its 10 year shelf life, based on the sampling rate of one sample per hour selected for the system. The system has been proven to be extremely reliable, and would have a very high MTBF. Therefore, the MTBF for the system was assumed to equal the MTBM of 1500 FH.

System feasibility includes non-recurring cost, recurring cost, and weight. Recall that the non-recurring cost is the cost to acquire the system, while recurring cost is the cost associated with maintaining the system. The acquisition cost for the system was found to be $40,000 [74]. Note that installation cost is not included, and would vary depending on where the data logger and sensors are placed inside the aircraft.. The AN101W system comes equipped with 8 sensors and one data logger. It was assumed that additional sensors would be needed, and thus a second complete system was added. This would provide a total of 16 sensors and two data loggers. Even with double the sensors and data loggers, the system cost is well below the target value of $100,000.

The recurring cost of the system is largely dependent on how often the sensors are replaced. The sensor may be replaced for two reasons. The first reason is that the sensor has been corroded through and needs to be replaced. The second reason is that the part that the sensor is attached to may need to be replaced, forcing the replacement of the sensor also. It is important to note that the sensors cannot be reused once they are attached to a surface. Therefore, once the sensor is removed, it must be replaced with a new one. For the purposes of calculating a recurring cost for the system, only replacement cost of the sensors and labor associated with maintaining the corrosion monitoring system were taken in to account.

The sensor is 100 μm thick [73]. Since the sensor itself is corroding, the amount of corrosion that the sensor experiences will influence how often it needs to be replaced. For a very low corrosion rate of 13 μm/year, the sensor would last 7.7 years before its thickness is corroded through. For an extremely high corrosion rate of 1 mm/year, the sensor would last about 1 month. For the purpose of calculating recurring cost of the system, a conservative estimate of 0.3 mm/year was assumed. Sensor cost is highly dependent on the number of sensors ordered. Assuming a high order of several hundred, the cost of one sensor would be approximately $5.00 [75]. If fourteen of the sixteen sensors are used to monitor corrosion, then a cost of $70 would be incurred every 3 months to replace the corrosion sensors. This equates to a yearly cost of $210.

If the data is downloaded once per month, then the estimated time required for using the system is 1 LMH per month, or 12 LMH per year, per system. If a labor hour is priced as $44, then $528 is required per year in labor. Adding the cost of replacing sensors to the cost of labor results in a total yearly cost of $738. Since a year can be represented as 300 FH, then the recurring cost of the system is $2.46/FH. This cost is far below the target of $10/FH. If the corrosion rate is not as high as the value used in this estimate, then the sensors will last longer before needing replacement, and the recurring cost will be even less.

The last item for consideration is total system weight. The weight includes the sensors, wiring, and data loggers. For a system with 16 sensors and 2 data loggers, the total weight comes to 2.2 lbs, which is well below the 10lb target value.

Table 14: System Evaluation

Category	Criteria	Target Value	Achieved Value
Capability	Sensitivity	0.01 mm/year	0.001mm/year
	Sampling Rate	0.00028 Hz	0.00028 Hz (1 sample/hour)
Dependability	Response Time	3 LMH	1 LMH
	MTTR	2 LMH	2 LMH
	MTBM	300 FH	300 FH
	MTBF	300 FH	300 FH
Feasibility	Non-Recurring Cost	$100,000	$40,000 (16 Sensors, 2 data loggers)
	Recurring Cost	$10/FH	$2.46/FH
	System Weight	10 lbs	2.2 lbs

The system evaluation was completed for the Analatom system using the values in Table 14. The achieved value was added into the requirement index equations developed earlier in this chapter, and the resulting values were calculated.

The first calculations were for capability, including sensitivity and sampling rate. Sensitivity is shown in Equation 10 and the sampling rate index is shown in Equation 11. Since the sensitivity of the design was much better than the requirement, the resulting index was much greater than 1. Since the sampling rate of the system could be set at the desired value of one sample per hour, the resulting index was equal to 1. This shows that the system is more than capable of meeting the requirements for capability.

$$Sensitivity\ Index = \frac{0.01\ (\frac{mm}{year})}{0.001\ (\frac{mm}{year})} = 10 \quad \textbf{Equation 10}$$

$$Sampling\ Rate\ Index = \frac{0.00028\ Hz}{0.00028\ Hz} = 1 \quad \textbf{Equation 11}$$

The next set of calculations were for dependability, including response time, MTTR, MTBM, and MTBF. The index for response time is shown in Equation 15. Actual response time for the system was less than expected, resulting in a large index value. The estimated MTTR of the system was the same as the requirement, resulting in an index equal to 1, shown in Equation 13. The same is shown with MTBM and MTBF, in Equation 14 and Equation 15 respectively. Overall, the requirements for dependability were achieved.

$$Response\ Time\ Index = \frac{3\ LMH}{1\ LMH} = 3 \quad \textbf{Equation 12}$$

$$MTTR\ Index = \frac{2\ LMH}{2\ LMH} = 1 \quad \textbf{Equation 13}$$

$$MTBM\ Index = \frac{300\ FH}{300\ FH} = 1 \quad \textbf{Equation 14}$$

$$MTBF\ Index = \frac{300\ FH}{300\ FH} = 1 \quad \textbf{Equation 15}$$

The last set of calculations were for feasibility, which included system costs and system weight. The non-recurring cost index is shown in Equation 16. The acquisition cost of the system was lower than expected, by more than half. The recurring cost of the system, shown in Equation 17, indicates that the cost per flight hour was much less than expected. Recall that the actual recurring cost will vary depending on the corrosive conditions experienced by the aircraft, which will influence how often the sensors need to be replaced. This factor drives the recurring cost, and may be lower or greater than the value shown here. The weight index, displayed in Equation 18, shows that the actual system weight was far less than the

10lb requirement. The recurring cost, non-recurring cost, and weight of the system were far lower than the requirement. Overall, the feasibility of the system was very high.

$$Non-Recurring\ Cost\ Index = \frac{\$100{,}000}{\$40{,}000} = 2.5 \qquad \textbf{Equation 16}$$

$$Recurring\ Cost\ Index = \frac{10\ \$/FH}{2.46\ \$/FH} = 4.0 \qquad \textbf{Equation 17}$$

$$Weight\ Index = \frac{10\ lbs}{2.2\ lbs} = 4.6 \qquad \textbf{Equation 18}$$

The values for each index were plotted in Figure 62. The requirement, shown in red, indicates the ideal value of 1 for each index. The design, shown in blue, indicates the actual index value for the selected system design. Index values equal to or outside the red circle are ideal. Index values inside the red circle did not meet requirements. It is clear that the selected monitoring system design exceeds all expectations.

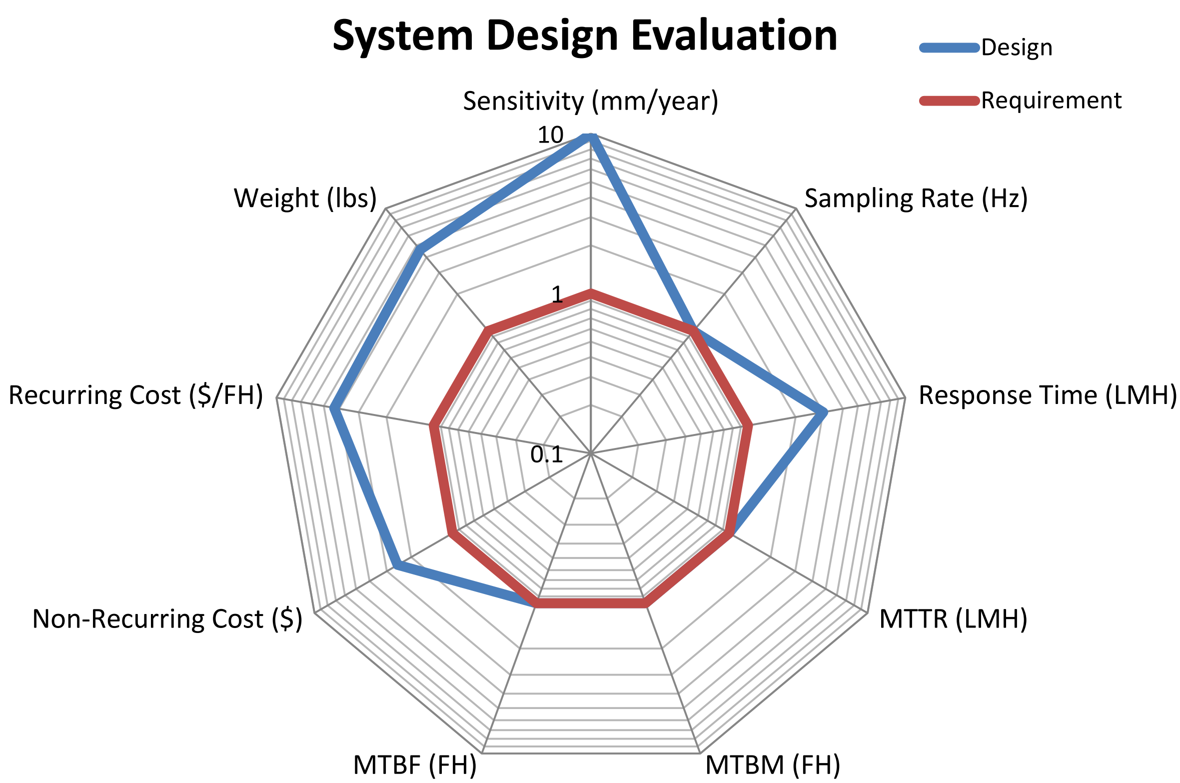


Figure 62: System Design Evaluation

One of the most important considerations for designing a monitoring system is its effectiveness. The system shown in this investigation was found to be capable, dependable, and feasible.

4.7 Make Decision

The AN101W was chosen to match the attributes that were selected from the matrix of alternatives. The system was evaluated against requirements, and was shown to meet the capability, dependability, and feasibility needs of the aircraft. Thus, the system represents a possible solution for implementing a corrosion monitoring system for the UH-1 helicopter. The system design process resulted in several findings that are discussed in the next section.

4.8 Findings

Developing a corrosion monitoring system design led to several findings relating to implementing the system as well as the system's impact on aircraft maintenance operations.

- The sensor only measures itself.
- The sensor sacrifices itself.
- Savings in cost and maintenance effort cannot be quantified until the system is implemented.
- The recurring cost of the system will not be known until the system is implemented.

The sensor does not take measurements of the structure directly. The sensor is made of the same material as the structural component, and would thus ideally corrode at the same rate, however, it does not provide information on the condition of the structure. This is due to the fact that the sensor only provides corrosion rate measurements from the corrosion that it experiences. The sensor is mounted to the structure, but is still isolated from the structure itself.

The sensor sacrifices itself. This is due to the fact that the sensor provides corrosion rate data from the corrosion it experiences. This means that eventually, the corrosion will make its way through the entire thickness of the sensor. Thus, the sensor must be replaced periodically, significantly increasing the cost of maintaining the system.

Benefits of using the system will not be seen until far after the system is installed. While a great deal of maintenance time can be saved by extending inspection intervals for structure that is difficult to reach, it would take some time to determine whether monitoring corrosion rates can lead to an accurate prediction of damage.

It is certain, that the corrosion monitoring system will assist in reducing the number of parts that need to be replaced, by providing early warning through its measurements. As found during the system evaluation, repairs comprised 37% of maintenance actions that involve corrosion, and took an average of 2 LMH to complete. Replacements, however, represented 63% of maintenance actions and took an average of 4.5 LMH to complete. It is likely that total number of replacements can be reduced through early detection. Major components that would have been replaced under the normal inspection procedures could be repaired instead. Making a repair takes far less time, as the component can be cleaned and does not need to be removed and replaced with another part. Not only does this save maintenance time, which is priced at $44/hour, but the cost of the part is also saved. This can add up quickly, as expensive replacements are avoided.

The recurring cost of the system will not be known until the system is implemented. This is due to the fact that the majority of the recurring cost will be a result of replacing sensors that have been corroded through. The sensor works by measuring its own corrosion. Depending on location, corrosion rates may be very high or very low, which will influence how long the corrosion sensors will last before they need to be replaced.

4.9 Recommendations

Findings from the system design resulted in three recommendations for system use and operations.

- Utilize both atmospheric and corrosion sensors.
- Inspection intervals should remain the same.
- Install one system per aircraft, as operating conditions vary, and atmospheric conditions are the main influence on corrosion rate.

The first recommendation is to use both atmospheric sensors and corrosion sensors together in a corrosion monitoring system. It is well known that atmospheric conditions have a major effect on the extent of corrosion damage. In the structural evaluation it was assumed that the corrosive conditions experienced by the aircraft were the same as that experienced by their assigned base. Detailed information on the usage of each aircraft during the analysis time period was not recorded along with maintenance actions. It would be more accurate to measure the atmospheric conditions inside the aircraft, where the structural components reside. Future structural evaluations after the system is implemented can then include accurate atmospheric data.

The second recommendation is to keep inspection intervals as they are, until the relationship between structural corrosion damage and operating conditions is better understood. Once trends are understood from the monitoring system data, inspection intervals can be tailored by aircraft location, or reduced to save labor time.

The third recommendation is to install one monitoring system per aircraft. As discussed previously, operating conditions may vary with each aircraft. Since atmospheric conditions are one of the main influences on corrosion rate, it would be best to monitor corrosion on an individual basis.

4.10 Summary

A corrosion monitoring system for the UH-1 aircraft was designed following the generic Integrated Product and Process development (IPPD) methodology. The methodology involved a six step top-down decision support process. The six steps included establishing need, defining the problem, establishing value, generating feasible alternatives, evaluating alternatives, and making the final decision. The primary goal was to develop a system that met user requirements.

To establish need, it was important to recognize the deficit in current methods and the gap to be bridged by this effort. As mentioned previously, corrosion is recognized as a prominent structural issue. Corrosion damage raises sustainment effort and money needed to keep the aircraft safe for flight. Early detection has several benefits that can be realized through a corrosion monitoring system.

In defining the problem, the desired traits of the desired system were determined and quantified. The seven management and planning tools were essential to this step of the IPPD methodology. The tools that were utilized in this investigation included the interrelationship diagraph, tree diagram, and prioritization matrices. First, user and engineering requirements were defined. A functional analysis was then performed to identify the operational, functional, and physical system functions and decomposition. The quality function deployment (QFD) was then used to analyze relationships between user requirements and engineering attributes.

Results of the problem definition section were used to develop a metric to determine how well the designed system meets the target objectives. Once the metric was developed, feasible alternatives were explored via a matrix of alternatives. It was found that over 2000 different system designs were possible. One particular design was selected among the alternatives as the conceptual system design. Actual performance of the system was compared with the original target objectives. The system of choice was the commercial off-the-shelf Analatom AN101W system. This system met and exceeded the objectives, making it the system of choice for the UH-1 aircraft.

This investigation showed that commercial off-the-shelf systems are available and affordable. The system proposed in this analysis was not flawless, however, and several weaknesses have been identified. Recommendations were made pertaining to the operation of the system and its impact on operations. Despite shortfalls, early warning through corrosion monitoring remains the next step in corrosion management.

CHAPTER 5: SYSTEM IMPLEMENTATION

5.1 Overview

Perhaps the most significant question raised in this investigation is: what impact will a corrosion monitoring system have on maintenance operations? What savings in maintenance effort and cost will be observed as a result of implementing the monitoring system? Answering these questions is the focus of this chapter of the investigation - system implementation.

5.2 System Installation

Once the decision is made to implement a corrosion monitoring system, system installation becomes the next focus. Recall that the system is composed of the following:

- 2 data loggers
- 16 sensors
- Wiring and batteries
- 1 data download device
- Software needed to display sensor readings

Everything except for the download device and the software will be installed on the aircraft. The majority of installation decisions will revolve around sensor placement. Sensors can be placed in areas that are most problematic, and in areas that are difficult and time consuming to inspect. Recall that maintenance data was analyzed to determine which areas of the aircraft were most impacted by corrosion damage. This was reflected in both the frequency of maintenance actions and the average MTTR for each area. Areas with the highest frequency and MTTR can be given priority for sensor placement. Consideration was also given to the size of the aircraft area, such that larger areas were assigned additional sensors.

It is important to note that it may not always be possible to place a sensor on the component of interest. The sensor may instead be placed near the component of interest, and still provide accurate corrosion rate data for that area.

Each aircraft area is displayed in Figure 63 from worst to best. Both frequency and MTTR were considered, and an overall rank was assigned to each damage area. Note that electrical components were omitted, as they do not contribute to the structural integrity of the aircraft.

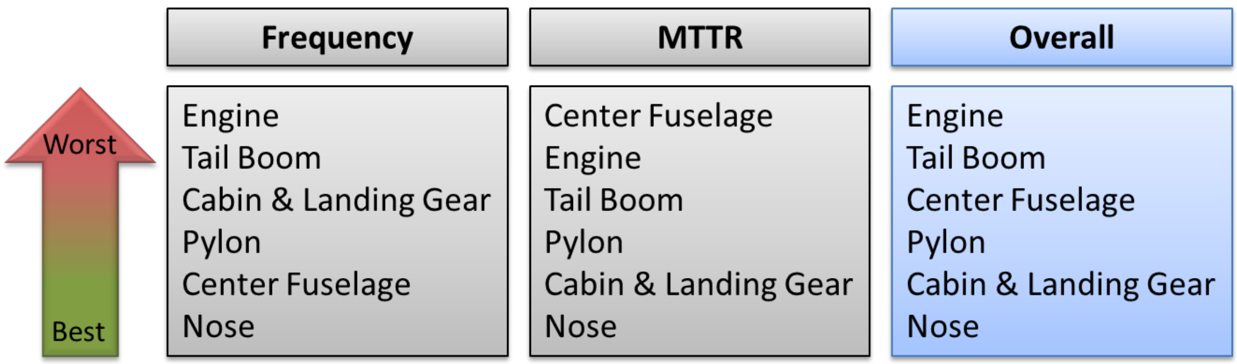


Figure 63: Aircraft Damage Ranking

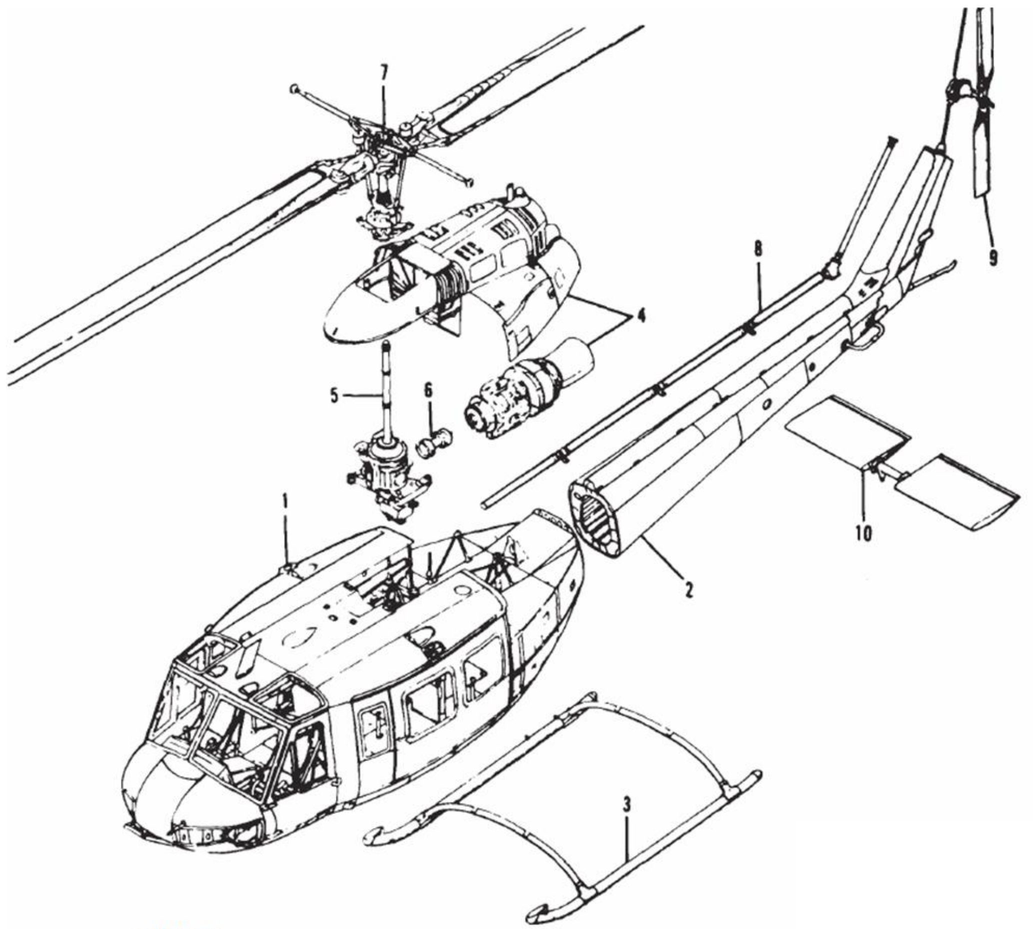
Once an overall rank of aircraft areas was established, the corrosion rate and atmospheric sensors were divided among the areas. Table 15 shows the recommendations for sensor distribution. The CMS contains a total of 16 sensors, which can either measure corrosion rate or atmospheric conditions. Of the 16 sensors, 14 were selected to measure corrosion and the remaining two were chosen to measure the atmosphere. Few atmospheric sensors were chosen, as it is of primary importance to monitor corrosion rates within the aircraft. Atmospheric sensors are still useful, as they provide an opportunity to compare damage data with climate data, for more advanced corrosion prediction capability.

Table 15: Sensor Distribution

Aircraft Area	Corrosion Sensors	Atmospheric Sensors	Total
Engine	4	0	4
Tail Boom	3	1	4
Center Fuselage	3	1	4
Pylon	1	0	1
Cabin & Landing Gear	2	0	2
Nose	1	0	1

Atmospheric sensors can measure temperature, humidity or time of wetness (TOW). For this application TOW sensors were chosen, as they incorporate both temperature and humidity. Specific placements for the sensors were recommended for each of the six aircraft areas.

Figure 64 shows a breakout of the major areas of the UH-1 aircraft. It was provided here for reference, as these areas of the aircraft will be shown in detail to describe the sensor configuration.



INDEX NUMBER	FIGURE TITLE
1	SECTION ASSEMBLY, HELICOPTER FORWARD
2	SECTION ASSEMBLY, HELICOPTER AFT
3	LANDING GEAR ASSEMBLY, SKID
4	POWER PLANT INSTALLATION
5	TRANSMISSION AND MAST ASSEMBLY
6	DRIVE SHAFT INSTALLATION, ENGINE TO TRANSMISSION
7	PYLON INSTALLATION
8	SHAFT INSTALLATION, TAIL ROTOR DRIVE
9	HUB AND BLADE ASSEMBLY, TAIL ROTOR
10	ELEVATOR INSTALLATION, SYNCHRONIZED

Figure 64: UH-1H Breakout

The first group of sensors was assigned to the aircraft engine area. This area is represented by index 4 on Figure 64. The engine, which ranked the worst overall, was given 4 corrosion rate sensors. Since the engine cowling, engine mounts, and control solenoid were frequently damaged by corrosion, sensors were placed in these locations.

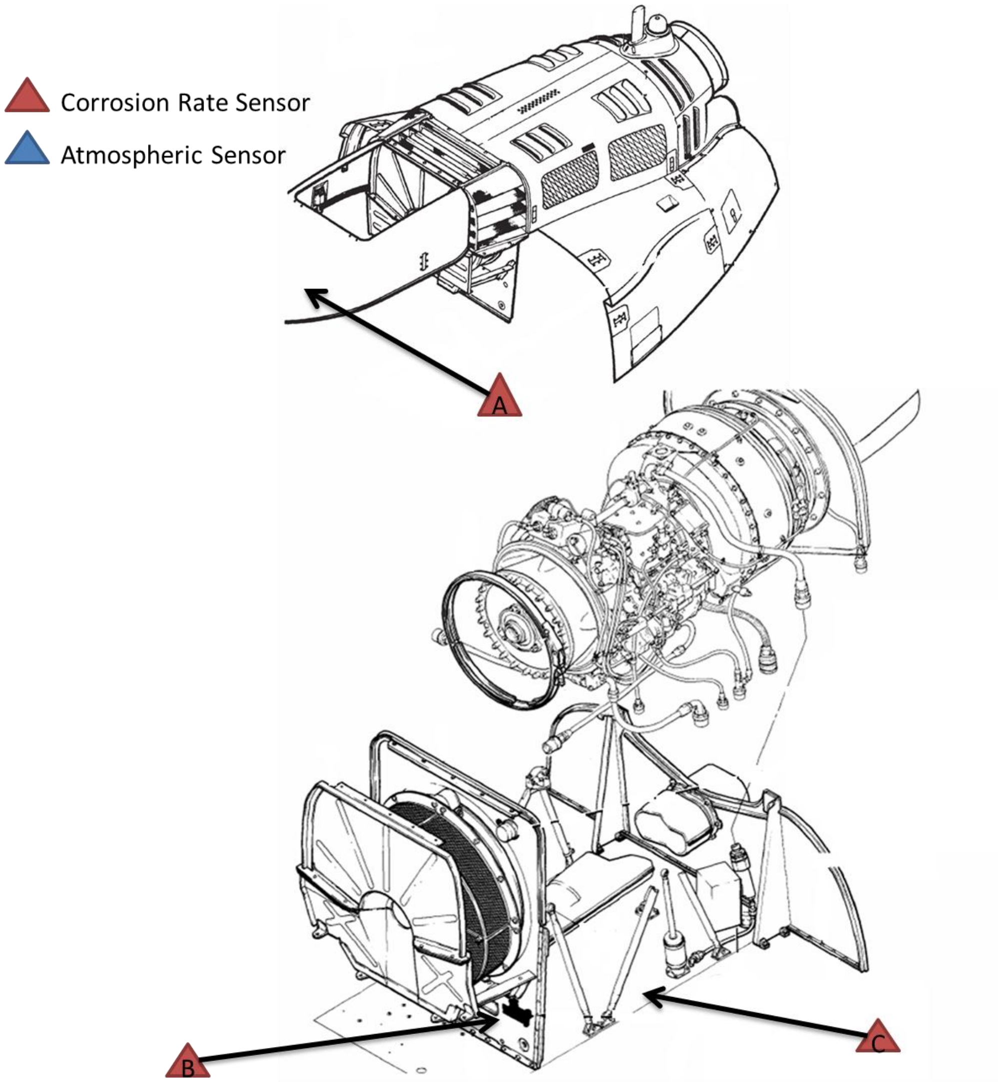


Figure 65: Engine Sensor Installation

Figure 65 shows the engine installation for the UH-1H aircraft. Corrosion rate sensors are shown as red triangles, and atmospheric sensors are shown as blue triangles. As shown in the figure, two sensors were selected for the cowling (A and B) and one was placed near the engine mounts (C). Figure 66 shows the engine controls installation. One sensor was placed on a bracket near the solenoid (D).

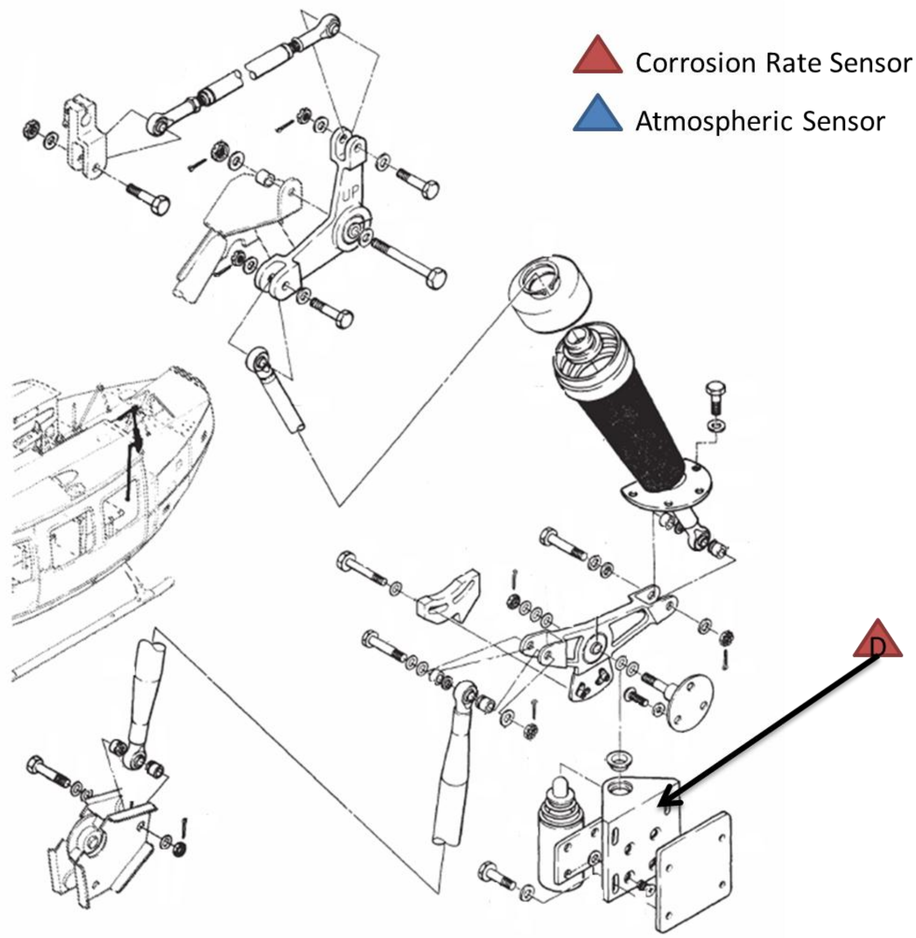


Figure 66: Engine Control Sensor Installation

The tail boom was the second most problematic area overall. This area was given 3 corrosion sensors and 1 atmospheric sensor. Atmospheric sensors were assigned to the largest areas of the aircraft, the tail boom and center fuselage.

The most frequent problems with the tail boom included the drive shaft and hangar assemblies. While a sensor cannot be installed directly on the drive shaft, it can be attached near the drive shaft. Figure 67 shows the sensor installation for the tail boom. Sensor A is attached to the aircraft just below the drive shaft. Sensor C was placed within the vertical fin structure, near the aircraft skin. Sensors B and D will monitor corrosivity and TOW inside the tail boom, respectively.

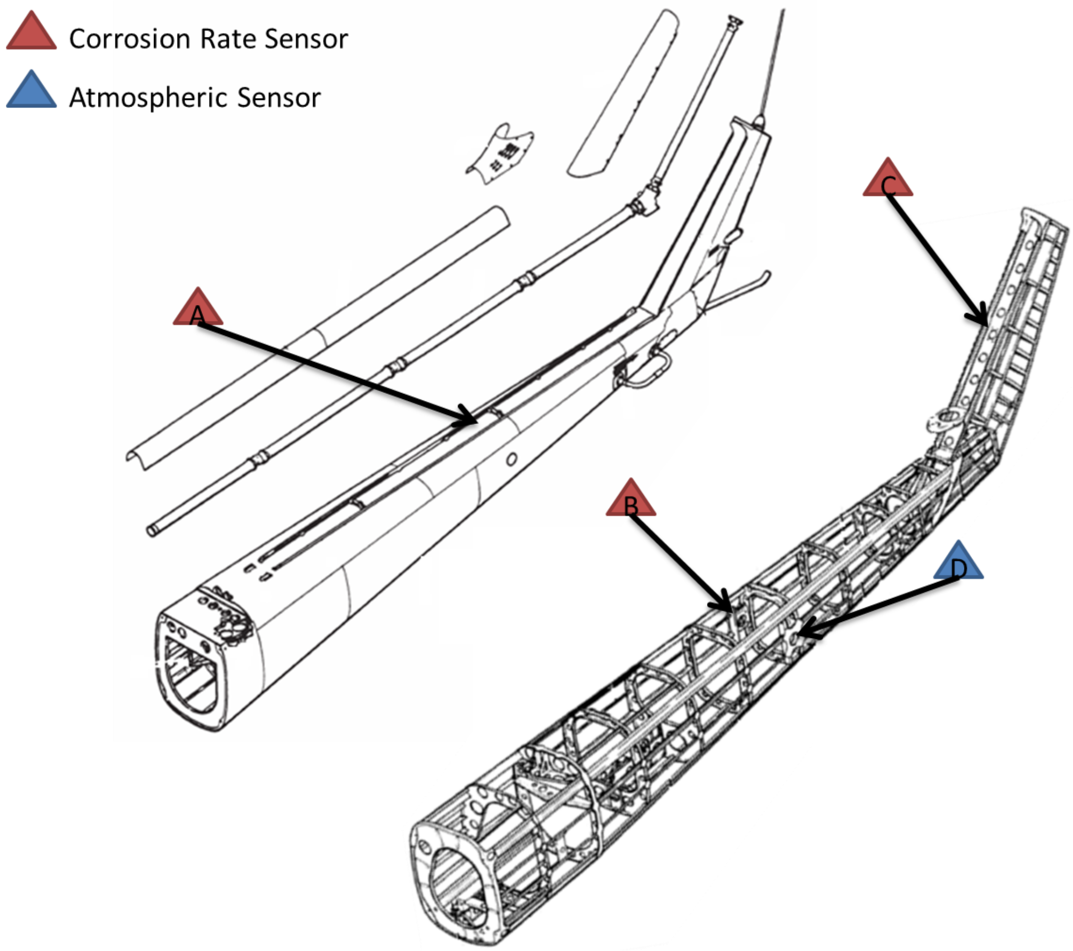


Figure 67: Tail Boom Sensor Installation

Similar to the tail boom, the center fuselage was given 3 corrosion rate sensors and 1 TOW sensor. The center fuselage contains multiple bulkheads and floor panels that make for excellent monitoring locations, as shown in Figure 68. One TOW sensor (D) was assigned to monitor the conditions under the floor panels in the center fuselage area. Two corrosion rate sensors were placed on the aft bulkheads (A and C), and one was placed on the end of center fuselage, where the tail boom is connected (B).

The pylon was given 1 sensor, as it represented a small area of the aircraft, and was low in overall ranking. It was recommended that the sensor be placed on the lift beam, as it is responsible for transferring the lift generated by the rotors down into the primary structure of the aircraft. Figure 69 shows the sensor installation location.

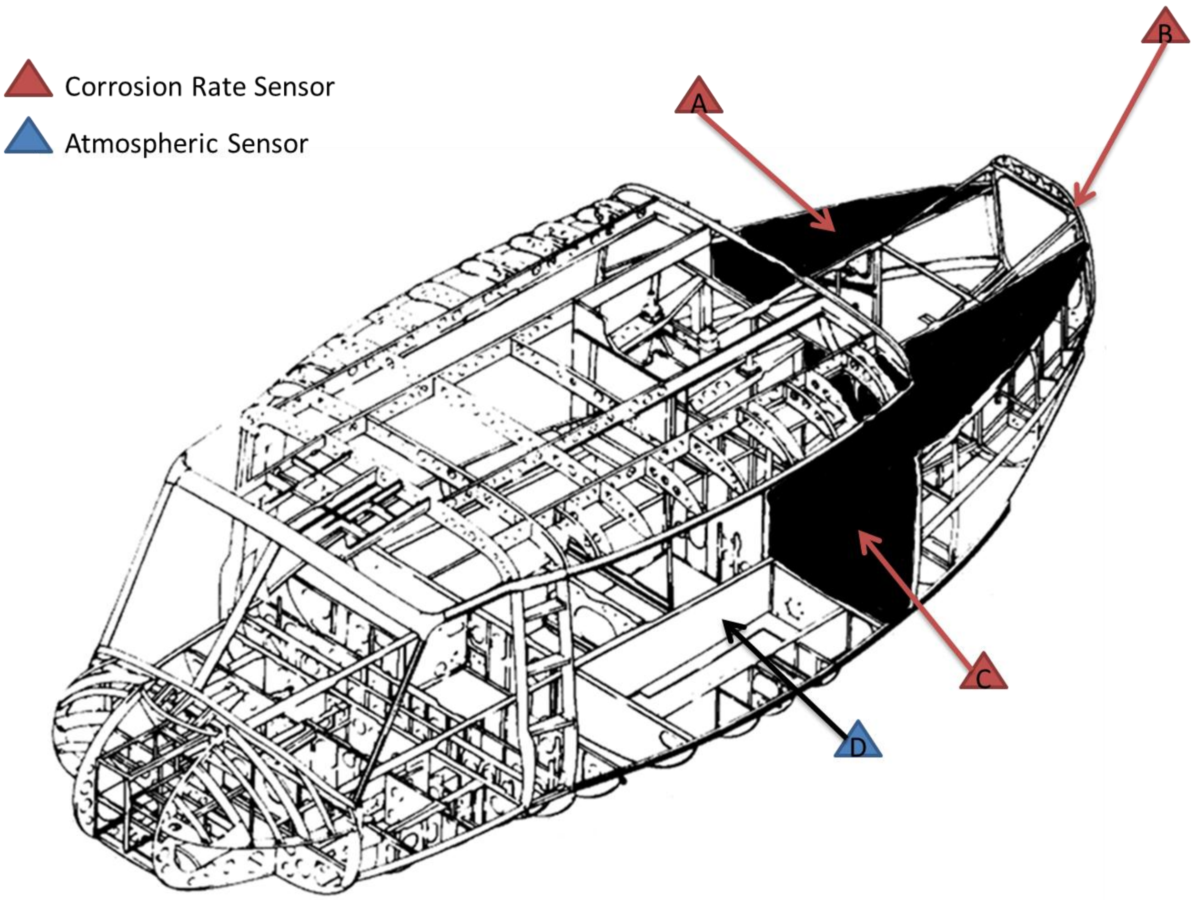


Figure 68: Center Fuselage Sensor Installation

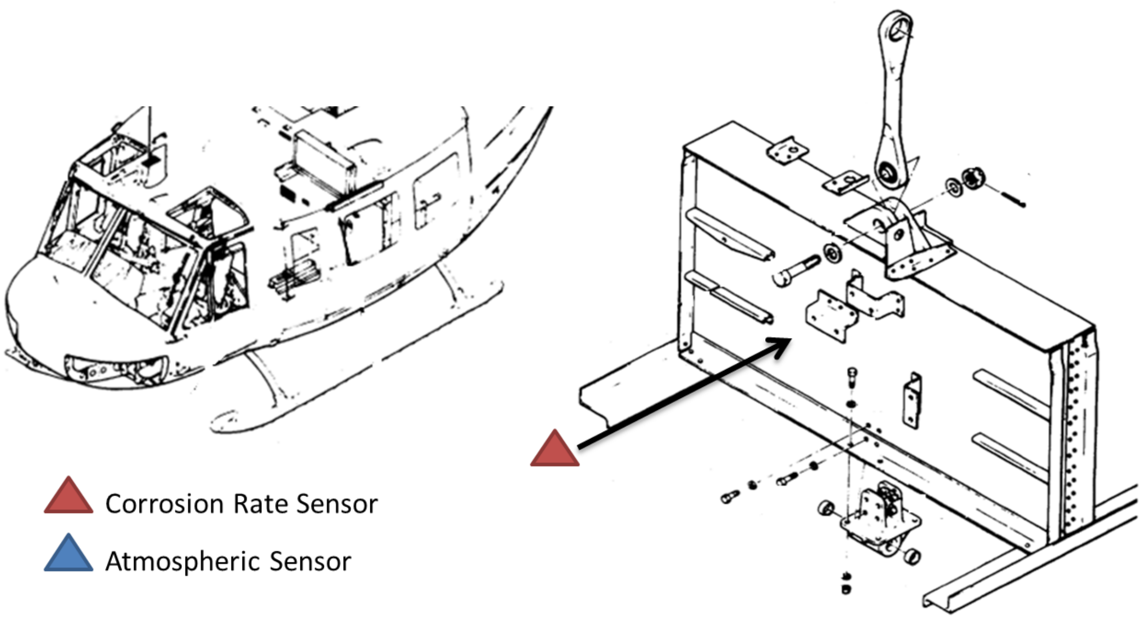


Figure 69: Pylon Sensor Installation

The cabin & landing gear section is a large area of the aircraft, and for that reason, it was given two corrosion sensors. Sensor installation is shown in Figure 70 and Figure 71.

Figure 70 shows a corrosion sensor installed on the outer skin of the aircraft, near the upper wire strike. Both the upper and lower wire strikes were a recurring problem throughout the six year study. Only one sensor could be afforded for monitoring the wire strikes, and thus only one wire strike could be monitored. The upper wire strike was chosen for sensor placement, as it was the most problematic of the two. Corrosive conditions for the lower wire strike, located on the bottom of the aircraft, can be inferred from readings provided by the upper wire strike sensor.

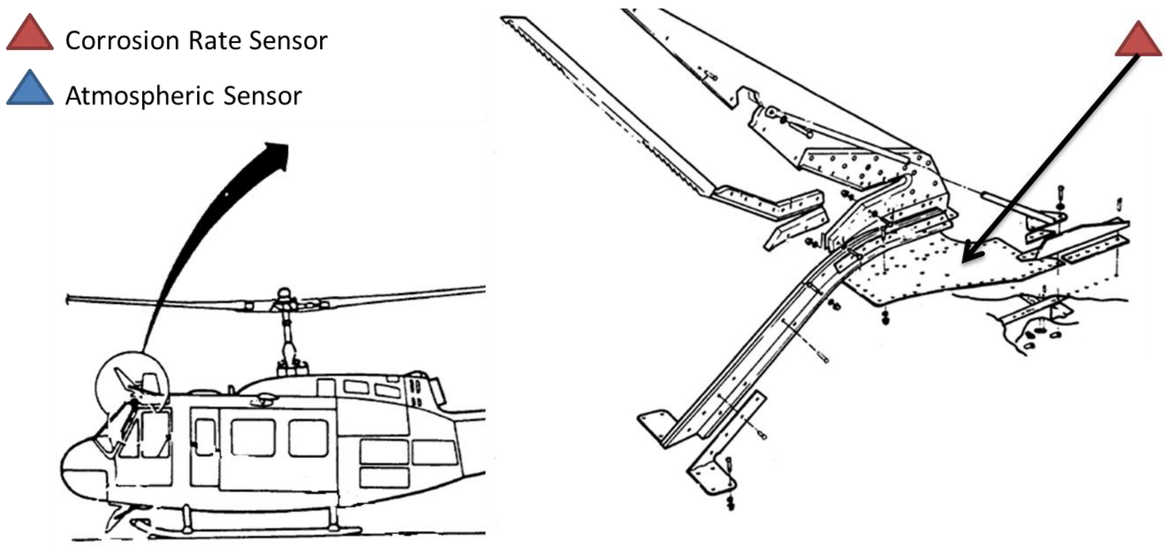


Figure 70: Upper Wire Strike Sensor Installation

The remaining corrosion rate sensor was placed inside the cabin, under the floor panels that are shown in the shaded portion of Figure 71. Floor panel corrosion was another common problem for this area of the aircraft. It is expected that floor panels are a problem, since this area of the aircraft receives the most 'traffic' from aircrews entering and leaving the aircraft. Depending on the mission, water may be inadvertently carried in by personnel, spurring the corrosion process. In addition to traffic, inspecting beneath the floor panels is time consuming, making this area ideal for monitoring.

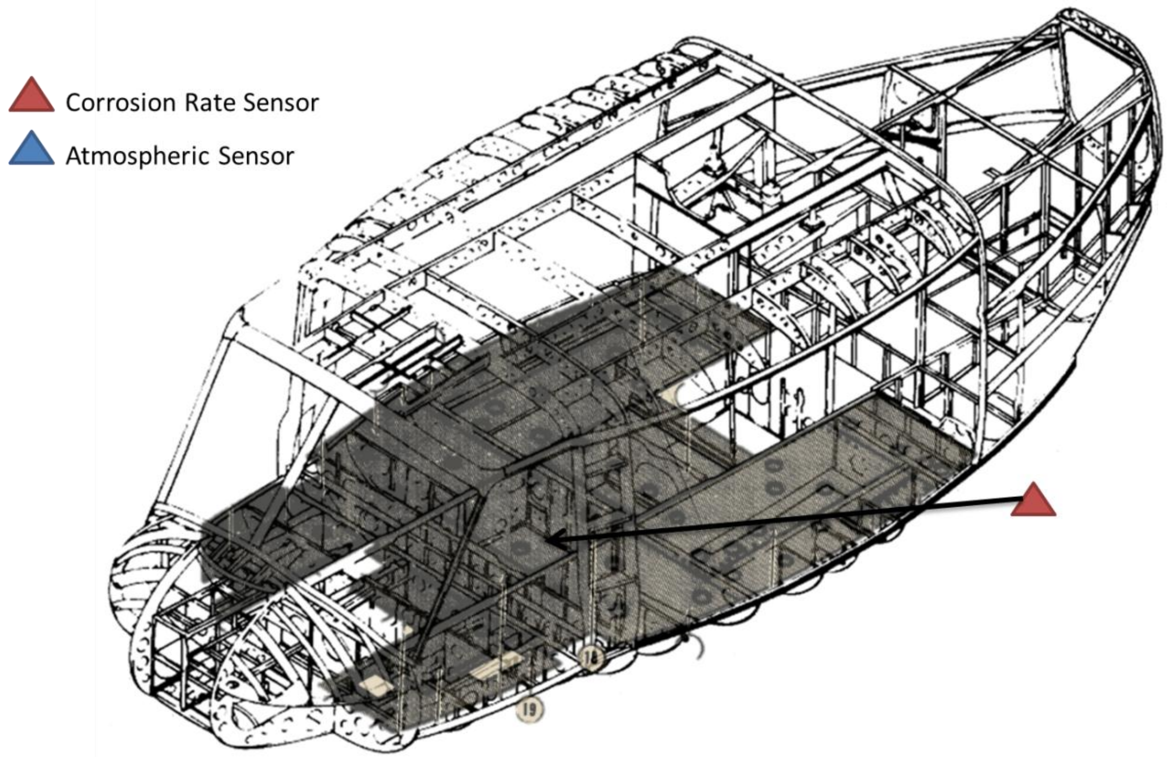


Figure 71: Cabin Floor Sensor Installation

The nose, which was least problematic and represented by a small area, was assigned 1 corrosion sensor. The sensor was placed on the underside of the nose door, as shown in Figure 72. It may seem at first glance that monitoring this area is unnecessary, however, it is likely that monitoring corrosion rates inside the nose structure near the avionics equipment will assist in predicting corrosion damage to the sensitive electronics.

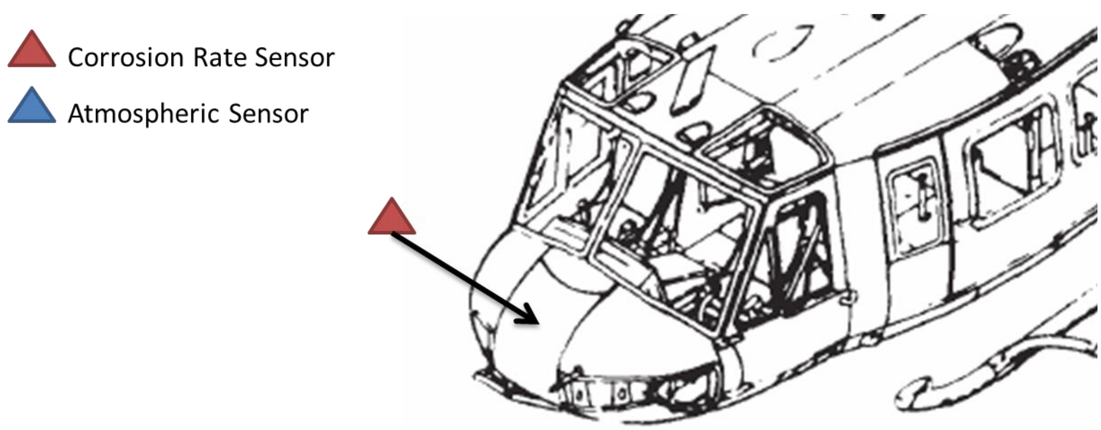


Figure 72: Nose Installation

Two data loggers are responsible for capturing the corrosion rate and atmospheric data provided by the 16 sensors. The placement of the data loggers can vary, however, they should be placed in a central area of the aircraft, so that excessive wiring is not required to reach each sensor. In addition, the data loggers themselves will need to be accessed occasionally, for battery or sensor replacement.

The recommended location of the data loggers is shown in Figure 73. Both loggers were placed in the center fuselage area. Since the loggers do not need to be accessed frequently, they can be placed out of the way of aircrews and other equipment. As long as the signal from the data logger is not blocked too much by the airframe, then the download process will proceed smoothly. Wiring that connects the sensors to the data logger may be easily placed along the structure of the aircraft, out of the way of aircrew operations.

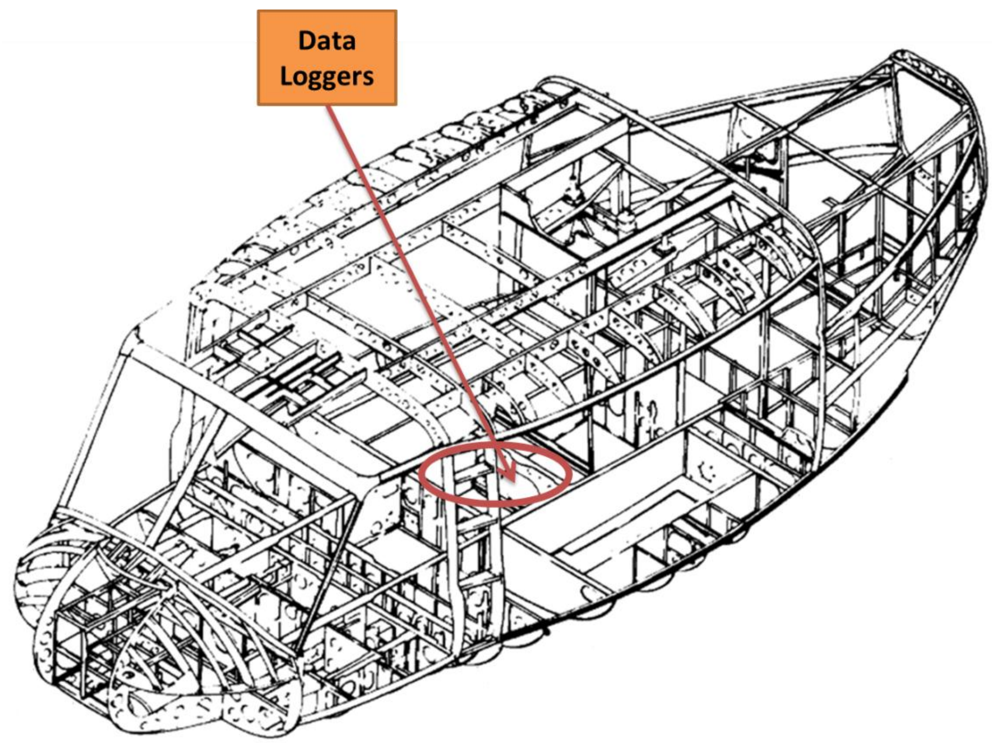


Figure 73: Data Logger Installation

The sensor and data logger placements shown here are recommendations, based on the maintenance data that was analyzed. Depending on the operation of the aircraft, a different sensor configuration may be needed. The corrosion monitoring system shown here is very flexible. Since the sensors are simply mounted on or near the structure of interest, they can be easily removed and placed elsewhere, if needed.

5.3 System Operation

Once the system is installed, it is ready to be used. Recall that one of the system requirements was a sampling rate of 0.00028Hz, or one sample per hour. This means that at every hour, each of the 16 sensors is sampled, and the data is stored by the data logger. It was estimated in the system design process that retrieving the data from the data loggers would need to occur about once each month. This equates to a total of 11520 samples, or 5760 samples per data logger, each month, per aircraft.

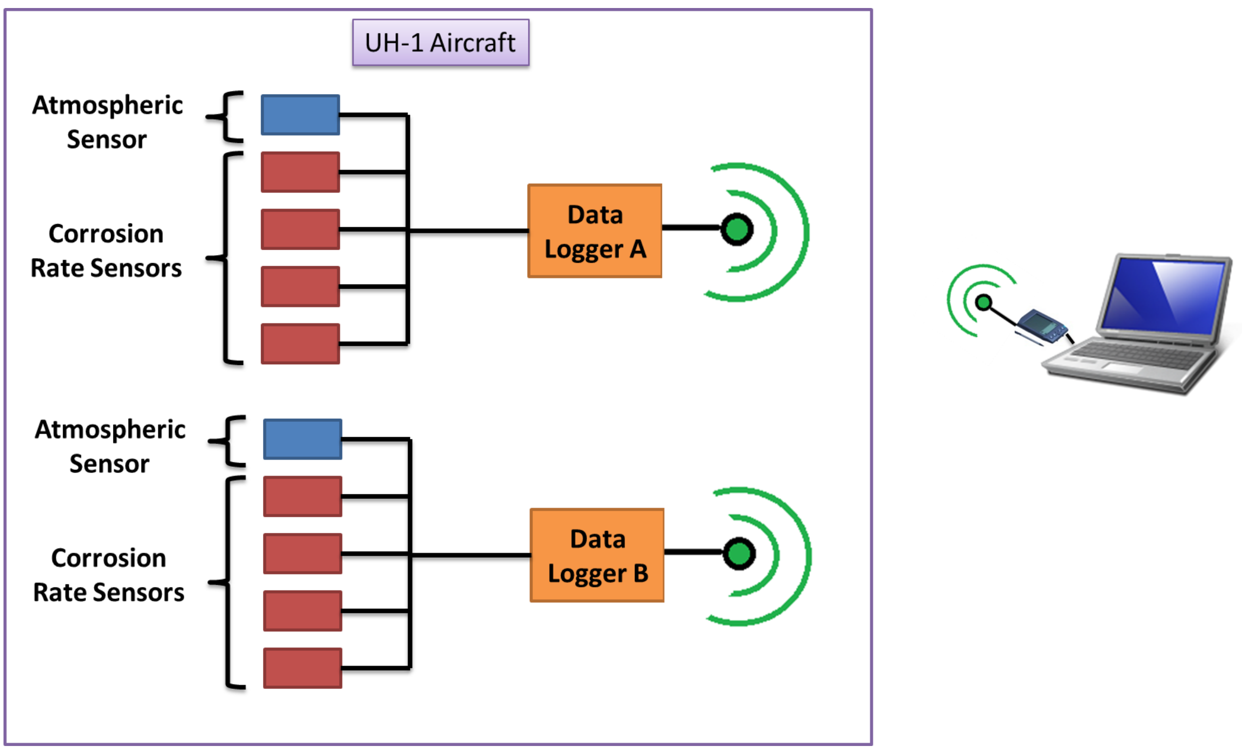
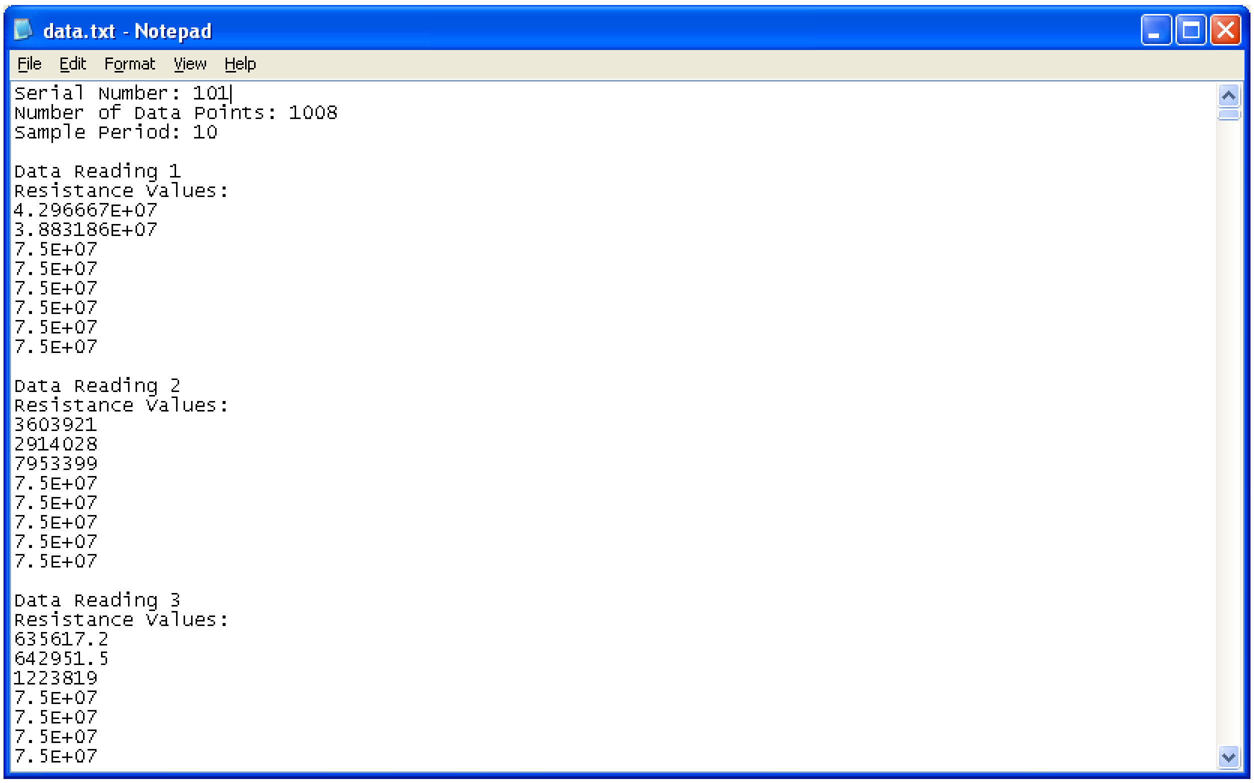


Figure 74: System Data Transfer

Since the data loggers can wireless transmit data, there is no need to access the data logger directly. Figure 74 depicts the data storage and download process. The data is wirelessly downloaded via a small handheld download device. Once the download is complete, the handheld device is connected to a computer where the data can be processed by the CMS software. The process of downloading data from the aircraft was estimated to take 5 minutes. The entire process of downloading data and processing it on the computer was estimated to take no longer than 1 LMH per month, or 12 LMH per year.

Figure 75 [78] shows an example of a downloaded data file. Note that the data is in the form of resistance values of the sensors. The data needs to be converted to corrosion rate by incorporating the resistance and material properties of the sensor. The sensor material is the same as the structure on which it is mounted, so depending on the application, sensors of different materials may be required.


data.txt - Notepad

File Edit Format View Help

```
Serial Number: 101
Number of Data Points: 1008
Sample Period: 10

Data Reading 1
Resistance Values:
4.296667E+07
3.883186E+07
7.5E+07
7.5E+07
7.5E+07
7.5E+07
7.5E+07
7.5E+07

Data Reading 2
Resistance Values:
3603921
2914028
7953399
7.5E+07
7.5E+07
7.5E+07
7.5E+07
7.5E+07

Data Reading 3
Resistance Values:
635617.2
642951.5
1223819
7.5E+07
7.5E+07
7.5E+07
7.5E+07
```

Figure 75: Sample Data File

The Analatom corrosion monitoring system is designed to minimize impact on aircrew workload. The sensors and data loggers are designed for unlimited life and do not require any inspection or maintenance. Thus, the majority of work will be in downloading data from the aircraft, which was minimized by incorporating wireless capability.

5.4 Aircraft Maintenance

The system may be designed to minimize aircrew workload, but what changes in maintenance inspection intervals or techniques can be expected? It was recommended during the system design that inspection intervals and techniques remain as they are, until the relationship between structural corrosion damage and operating conditions is better understood. Once trends are understood from the monitoring system data, several opportunities may emerge. First, inspection intervals can be tailored by aircraft location or operation. Aircraft in less corrosive environments can afford fewer inspections than aircraft in more corrosive environments. This would result in customization of inspections for each individual aircraft.

Second, the number of replacements that occur due to corrosion damage would be reduced. This is due to the advanced warning capability that the monitoring system provides. With damage trends more understood, the opportunity to make a repair increases. Recall that currently, replacements occur twice as often as repairs and take an average of twice as long to fix. Reducing replacements results in a reduced labor cost and part cost. When maintenance labor decreases, aircraft downtime also decreases. The result is increased aircraft availability and reduced maintenance cost.

Third, with prediction capability, component time change intervals can be specified to match actual corrosion rate data. This corresponds to the ability to accurately predict when components need to be replaced. The result is a reduction in unplanned maintenance resulting from corrosion, which in turn increases aircraft availability even more.

All three opportunities point to reduced maintenance effort for dealing with corrosion damage and increased aircraft availability, but what savings in maintenance cost can be expected? This question can only be answered after the system is implemented, and the relationship between corrosion damage and operating environment is better understood.

5.5 Summary

This chapter addressed the corrosion monitoring system installation and operation. Recommendations were made for both corrosion rate and atmospheric sensor placement on the UH-1 aircraft structure. Impact of the system on aircraft operations was discussed, and it was found that the system would require only 12 labor hours per year. The CMS sensors and data loggers require no inspection or maintenance. This factor combined with a low acquisition cost make this system highly recommendable for UH-1 usage. Once the system is implemented, several possibilities may emerge. Customized inspection intervals as well as reduced replacements result in decreased maintenance burden and increased aircraft availability to meet warfighter needs. Only after the system is implemented, can true savings in cost be evaluated.

CHAPTER 6: CONCLUSIONS & FUTURE WORK

6.1 Conclusions

Aging aircraft require increased sustainment effort, resulting in increased maintenance burden and cost. It is becoming increasingly important for corrosion management to be updated with more advanced techniques. Currently a reactive approach to corrosion is used, in which damage is dealt with on a find-and-fix basis. Corrosion inspections are normally qualitative, and the assessment of the structure is highly dependent on the examiner. As a result, this current technique has several shortfalls. The examiner's experience may be limited, there is a constant fluctuation of corrosive conditions, and corrosion damage often occurs in hidden areas of the aircraft [61].

Early detection is the next logical step in structural health management. Through corrosion monitoring, structural and environmental conditions can be closely observed, preventing excessive maintenance action and saving cost.

Aircraft maintenance data was analyzed to determine the most problematic areas of the aircraft, and the impact of aircraft location on corrosion damage. A method for analyzing maintenance information was developed, by converting the information into numerical data. Variables of influence and metrics were determined for model development. Four models were created, that would assist in determining what corrosion damage an aircraft can expect, given varying operating conditions. Although model creation was successful, model evaluation revealed all models to be unusable. The impact of aircraft location on corrosion damage could not be determined. Although a reliable prediction model could not be created, trends observed in the data were still valuable for identifying problematic areas of the aircraft.

Utilizing a corrosion monitoring system can provide the accurate corrosion data needed for the development of better prognostic models. Ambiguities due to the subjective nature of maintenance data can be eliminated by gathering corrosion rate data directly. Empirical data gathered from the UH-1 fleet can be studied and used to develop an understanding of the relationship between corrosion damage and operating environment.

A custom corrosion monitoring system was designed for the UH-1 aircraft utilizing the IPPD methodology. The requirements for the system were developed for the user and for the engineer. Available technology for corrosion monitoring systems was found and used to construct a design concept. The most beneficial design was found by evaluating multiple system alternatives against the original requirements.

System implementation was also investigated, which incorporated system installation and operation. Recommendations were made for both corrosion rate and atmospheric sensor placement on the UH-1 aircraft structure. Impact of the system on aircraft operations was discussed, and it was found that the system would require 12 labor hours per year. The CMS sensors and data loggers require no inspection or maintenance. This factor combined with a low acquisition cost make this system is highly recommendable for UH-1 usage.

Once the system is implemented, several possibilities for inspection changes may emerge. Customized inspection intervals as well as reduced replacements result in decreased maintenance burden and increased aircraft availability to meet warfighter needs. Once inspection intervals are customized, savings in maintenance effort and cost can be evaluated.

The selected commercial system proved to meet and exceed expectations, making it an ideal choice for the UH-1 aircraft. The system is not flawless, however, and several weaknesses have been identified. Despite system limitations, corrosion monitoring remains the next step in corrosion management, and will pave the way for more advanced corrosion management techniques. Through more advanced corrosion management techniques, the UH-1 aircraft will be safer and more available to meet growing warfighter needs.

6.2 Future Work

This study involved analyzing maintenance data that was not meant to provide accurate corrosion monitoring data. Several recommendations were made to improve the quality of data that is mined from the Air Force maintenance database. Recommendations include studying all work unit codes when data mining, and modifying maintenance data entry to include part numbers and multiple how malfunctioned codes. With these modifications, future corrosion data studies can provide more accurate corrosion damage and cost information.

The next major step in corrosion management is to implement corrosion monitoring systems, and acquire the level of detail needed to analyze trends in corrosion rate and atmospheric conditions. It is recommended that one corrosion monitoring system be installed per aircraft, since aircraft at different locations and with different utilization will have different corrosion rate trends.

Data from both corrosion and atmospheric sensors should be analyzed together, as it has been clearly shown in previous studies that atmospheric conditions have a large effect on corrosion rate. Data mining should continue while the system is in place so that damage data is studied along with data from the monitoring system. Until aircraft damage can be predicted, aircraft inspection intervals should remain the same.

Once the system is implemented, inspection intervals can be optimized for each individual aircraft, resulting in decreased burden and increased aircraft availability.

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